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IDENTIFICATION OF *OXYGENEUM PULVERULENTUM* FORBES, FROM ILLINOIS, AS A HYBRID CYPRINID FISH*

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ONE of the most disturbing problems that confront taxonomists pertains to nominal forms which, because of inadequate material or description, are not placeable in the systematic structure. It is now possible to remove one more of these uncertain forms from the list of American fresh-water fishes. Its interpretation as an intergeneric hybrid provides the occasion for adding another combination to the list of known natural hybrids. Further light is thrown on the characteristics of such hybrids, as compared with the parental species.

NOMINAL SPECIES AND COMPARABLE MATERIAL

Oxygeneum pulverulentum Forbes (1885: 136–137) was named as a new genus and species on the basis of a single specimen collected in the Illinois River at Peoria, Illinois, in June, 1878. Since the characters ascribed to this individual agree with those of no known genus or species, *O. pulverulentum* was recognized by Jordan and Evermann (1896: 207) and in various checklists and manuals. Since Large (1903: 14) suggested that the name might have been based on a hybrid, *O. pulverulentum* has been dropped from accounts of Illinois fishes (Forbes and Richardson, 1909; O'Donnell, 1935).

Through the courtesy of Mr. Philip W. Smith we have been able to study the unique type of *O. pulverulentum*, No. 28378–7050–331 in the collection of the Illinois Natural History Survey. The specimen is now identified as a hybrid of the combination *Campostoma anomalum pullum* × *Chrosomus erythrogaster*. This determination was confirmed by a comparison of the type with three well-preserved specimens of the same interspecific cross in the Museum of Zoology of the University of Michigan, with data as follows:

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* Contributions from the Scripps Institution of Oceanography, New Series, No. 555, and from the Museum of Zoology, University of Michigan.

Campostoma anomalum pullum × *Chrosomus erythrogaster*

No. 100971 (Pl. I, Fig. 1): tributary to Turkey River, T. 90 N., R. 4 W., Elk Township, Delaware County, Iowa; August 7, 1932; Carl L. and Laura C. Hubbs.

No. 103132 (Pl. I, Fig. 2): Spring Creek, tributary to Grand River, on highway 33, at Kansas, Delaware County, Oklahoma; September 12, 1935; C. L. Hubbs and Milton B. Trautman.

Campostoma anomalum plumbeum × *Chrosomus erythrogaster*

No. 122039 (Pl. I, Fig. 3): spring-fed creek on "Doc" Wagner's farm, Riley County, Kansas; September 21, 1927; L. O. Nolf.

The determination of the type of *Oxygeneum pulverulentum* and these three other specimens is made on the basis of morphological characteristics, supplemented by zoogeographical and ecological considerations. Such criteria, useful in the recognition and identification of natural hybrids, have been reviewed recently (Hubbs, Hubbs, and Johnson, 1943: 11–14).

MORPHOLOGICAL AND GENETIC CONSIDERATIONS

The presumed parental species agree in anatomical features that are associated with an herbivorous diet: the peritoneum is black, the gut is extremely long and convoluted, the pharyngeal teeth have a well-developed grinding surface and, typically, are confined to the main row. Nevertheless, these species are very dissimilar. Several authorities have gone so far as to place them in different subfamilies, but this has been an unnecessary and probably unjustified treatment. The former association of these genera with European groups of herbivorous genera, as by Jordan and Evermann (1896: 202), is now discredited. Both are probably members of the large North American group of leuciscine cyprinids. It is presumed that the two types have developed herbivorous adaptations independently and that they are not very closely related.

The four specimens interpreted as hybrids are compared below with the parental species in respect to several differentiating characters.

Pharyngeal teeth.—The number of pharyngeal teeth in each of the four hybrids, 5–4 (5 in the left side, 4 on the right), confirms the identification and is essentially intermediate. *Chrosomus erythrogaster* is one of the four species of Illinois minnows that may have 5 teeth in the main row. None of the others (*Opsopoeodus emiliae*, *Notemigonus crysoleucas*, and *Semotilus atromaculatus*) closely resembles the hybrid. The formula for *Chrosomus erythrogaster* is typically 5–5, occasionally 5–4 or 4–4; often with a single tooth in the lesser row on either side or on both sides. *Campostoma anomalum* has, consistently, only 4–4 teeth. In the original account of *O. pulverulentum* the teeth were reported to be 5–5, but we found that the right arch had never been removed and that it has only 4 teeth.

Gill rakers.—The contention that *C. anomalum* is one parent of *pulverulentum* as well as of the three other hybrids receives very strong support from the number of gill rakers (Tables I–II). Among the cyprinids of Illinois only two species have many rakers. *Notemigonus crysoleucas* as well as *C. anomalum* has numerous elongate rakers, but it differs so much in so many ways as to be eliminated as a possible parental species. In this respect the hybrids, though clearly intermediate, are somewhat closer to *Chrosomus* than to *Campostoma*. The limited data are suggestive of partial dominance of the smaller number of rakers.

Mouth and lips.—The mouth and lip structures are particularly critical in the identification. The mouth in *C. erythrogaster* is of normal cyprinid form: it is slightly oblique, forming an angle of about 25° with the horizontal, has thin lips, and has the mandible deeply U-shaped as viewed from below. The mouth of *C. anomalum*, in contrast, is greatly modified, presumably as an adaptation for the scraping of algae from the substratum. It is slightly oblique, but the lips are thick, especially so posteriorly. The mandible is truncate and the mouth is broad and nearly semicircular as seen from beneath. The cutting edges of the jaws are much enlarged. That of the lower jaw forms a broad, horizontal, shelflike projection, which is visible from below. The dentary itself is much flattened and expanded anterolaterad and forms a sharp edge distally. In describing *pulverulentum* Forbes wrote "lower jaw thin, with a sharp, hard edge," a characterization that is applicable among Illinois minnows only to *C. anomalum* or to a hybrid involving this species as one parent. The structure of the mouth is very similar among the four hybrids. The

TABLE I

COMPARISON OF *CAMPOSTOMA ANOMALUM*, *CHROSOMUS ERYTHROGASTER*, AND FOUR HYBRIDS BETWEEN THESE SPECIES

Data for *C. anomalum pullum* are based on 10 specimens (from U.M.M.Z. No. 130236) from Clear Creek, 1.5 miles south of Alto Pass, Union County, Illinois; those for *C. erythrogaster* on 10 specimens (from U.M.M.Z. No. 116413) from Shoal Creek, 6 miles west of Exeter, Barry County, Missouri. See text for source of hybrids. Mean values are given in parentheses.

Character	*Campostoma anomalum*	Hybrids				*Chrosomus erythrogaster*
		Illinois	Iowa	Kansas	Okla-homa	
Standard length (mm.)	50–76	64	56	49	29	47–63
Gill rakers*						
First arch						
Upper limb	7–11 (8.9)	4	5	6	5	2–3 (2.7)
Lower limb	21–25 (23.1)	12	13	12	15	8–9 (8.7)
Total	29–34 (32.0)	16	18	18	20	10–12 (11.4)
Second arch						
Upper limb	11–13 (11.6)	7	5	5	5	3–4 (3.4)
Lower limb	30–35 (31.9)	19	19	19	22	13–15 (14.1)
Total	41–47 (43.5)	26	24	24	27	17–19 (17.5)
Scale rows						
Along body	45–53 (49.5)	57	57	62	59	74–80 (77.1)
Around body	38–45 (41.6)	55	59	57	51	68–80 (75.0)
Around caudal peduncle	20–22 (20.2)	25	25	25	23	26–35 (30.5)
Lateral line						
Pored scales	45–52 (48.8)	57†	57†	52†	. .	15–29 (21.4)
Unpored scales	0–2 (0.7)	0†	0†	10†	. .	47–62 (55.7)
Per cent scales pored	96–100 (98.6)	100	100	84	. .	19–38 (27.8)
Index, dorsal fin position‡	.887–1.007 (.939)	.914	.846	.927	.910	.805–.938 (.862)
Anal rays	6–7 (6.9)	7	7	8	7	7–8 (7.9)

---

* Gill rakers were counted on the anterior face of the first and second arches, on the right side. All rudiments were included. A raker at the angle, if present, was included with those of the lower limb.

† As noted on page 150, the mean values and hybrid indices for pored and unpored scales would not necessarily be expected to be intermediate.

‡ This index is the distance from the origin of the dorsal fin to the caudal base divided by the predorsal length.

TABLE II

ANALYSIS OF MERISTIC COUNTS AND OF DORSAL FIN POSITION IN HYBRIDS, *CAMPOSTOMA ANOMALUM* × *CHROSOMUS ERYTHROGASTER*, AND THE PARENTAL SPECIES

The mean values for the four hybrids are compared with expected values, determined as arithmetic means of the figures for the parental species. The difference is indicated by the plus sign (+) where it approaches *Chrosomus*, by the minus sign (−) where it is closer to *Campostoma*. The hybrid indices are computed with mean values arbitrarily set for *Chrosomus* at 0 and for *Campostoma* at 100. Data from Table I.

Character	Mean number or ratio			Hybrid index	
	Expected	Observed	Difference	Range	Mean
Gill rakers					
First arch					
Upper limb	5.8	5.0	−0.8	21–53	37
Lower limb	15.9	13.0	−2.9	23–44	30
Total	21.7	18.0	−3.7	22–42	32
Second arch					
Upper limb	7.5	5.5	−2.0	20–44	26
Lower limb	23.0	19.8	−3.2	28–44	32
Total	30.5	25.3	−5.2	25–37	30
Scale rows					
Along body	63.3	58.8	−4.5	60–73	68
Around body	58.3	55.5	−2.8	48–72	61
Around caudal peduncle	25.4	24.5	−0.9	53–73	61
Lateral line					
Pored scales	35.5*	55.3*	+19.8*	103–130	121*
Unpored scales	28.2*	3.3*	−24.9*	83–101	95*
Per cent scales pored	63.2	94.7	+31.5	79–102	94
Index, position of dorsal fin†	.901	.899	−.002	−21–84	48
Anal rays	7.4	7.25	−0.15	−10–90	65
Average hybrid index of all characters				46–56‡	52‡

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* As noted on page 150, the mean values and hybrid indices for pored and unpored scales would not necessarily be expected to be intermediate.

† This index is the distance from the origin of the dorsal fin to the caudal base divided by the predorsal length.

‡ In computing the average hybrid index of all characters for each hybrid specimen and the grand average index for all specimens, we have excluded the total gill-raker counts and, as noted on page 150, the number of pored and unpored scales

lips are moderately thickened, fleshier than in *Chrosomus*, but thinner than in *Campostoma.* The mouth is notably wider anteriorly than in *Chrosomus*, but has a greater axial length than in *Campostoma.* The cutting ridges (and dentaries) are wider and flare outward more than in *Chrosomus*, but are less expansive than in *Campostoma.* The hybrids agree with both parental species in lacking barbels. In overall form, the mouth and lips present a nice pattern of intermediacy between *Campostoma* and *Chrosomus.* Very similar intermediacy in mouth characters is shown by the hybrid *Acrocheilus alutaceum* × *Ptychocheilus oregonense*, which has also been regarded as a distinct species and even genus (Hubbs and Schultz, 1931).

Scales.—One of the most compelling reasons for regarding *pulverulentum* as a hybrid involving *Chrosomus* pertains to the basal radii on the scales. Among native cyprinids from Illinois primary radii are lacking on the anterior field of the body scales except in *C. erythrogaster* and the species of *Rhinichthys.* In the type of *pulverulentum* and in the other hybrids the anterior field has a few irregular and malformed radii and the focus is nearer the anterior margin than in *Chrosomus*, but less close than in *C. anomalum.* Such a condition could arise in a *Campostoma* × *Rhinichthys* hybrid, but other characters render that interpretation of the specimens quite implausible.

C. erythrogaster has tiny scales, whereas those of *C. anomalum* are of moderate size. The difference between these species is marked and, presumably because of the mode of inheritance, the counts for the four hybrids lie between the most closely approaching counts of the parental species with no overlap in any of three indices (Tables I–II). In scale counts the hybrids are slightly closer to *anomalum* than to *erythrogaster.* Partial dominance of high scale number is suggested, but not clearly proved, in view of the small sample size, the heterogeneity of the stocks, and the known geographical variation in scale size in *anomalum* (Hubbs and Greene, 1935: 90–94).[1]

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[1] As printed, Table II of the paper by Hubbs and Greene, summarizing data on variation in scale counts in two subspecies of *anomalum*, requires clarification (proofs were not referred to the authors). The column heading "Alone" applies to the last column only for *oligolepis* and to the first two columns for *pullum.* A line or space should have been inserted to separate the counts for scales around the body from the counts for lateral-line scales. This line should have been drawn between the rows labeled 39 and 40 for *oligolepis* and should, of course, have passed below all figures in the column headed "Around body" and above all figures in the column headed "Lat.

The type of *pulverulentum* has a complete lateral line with 57 scales, not 63, as reported by Forbes.

Lateral line.—If hybrids were always perfectly intermediate between their parental species in all characters, the development of the lateral line in these specimens would preclude their identification as hybrids involving *erythrogaster*, in which species the line is short (Table I). The evidence suggests that the reduction or loss of the lateral line, a common occurrence in spring-inhabiting or other quiet-water fishes such as *Chrosomus*, is here under the predominant or complete control of a single recessive gene. Hence the heterozygotes have the canal almost or quite complete, as in *Campostoma.*

Position of dorsal fin.—In the hybrids, on the average, the origin of the fin is midway between the mean positions in the parental species (Tables I–II). In *Chrosomus* the dorsal fin is placed more posteriorly than in *Campostoma.*

Anal rays.—The fact that three of the four presumed hybrids have only 7 principal anal rays (Table I), the minimum modal number in known American cyprinids, makes it highly probable that, if they are really hybrids, one parental species typically has 7 anal rays (as *anomalum* does) and the other probably has not more than 8 (the typical number in *erythrogaster*).

Digestive tract.—In the hybrid interpretation it is significant to note that *Campostoma* is unique among all known fish genera in that the double loops of its greatly elongate intestine completely encircle the air bladder. In *C. erythrogaster*, on the other hand, the gut is shorter, and the convoluted loops lie mostly in the ventral part of the body cavity. Forbes' original characterization of *pulverulentum* as having the "peritoneum black, intestine long, twice or more the length of head and body . . . ." indicates that one or both of the parents were "herbivorous" species. The cyprinids of Illinois with a long gut are referable to the genera *Chrosomus*, *Hybognathus*, *Dionda*, *Pimephales* (including *Hyborhynchus*), and *Campostoma*, and of these only *Chrosomus* and *Campostoma* suggest the hybrid. Unfortunately, the type of *pulverulentum* has been eviscerated, and the body is so faded that the peritoneum now appears silvery. In the

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line." To the right of the latter column it should have passed between the rows labeled 47 and 48. Another line or space should have been inserted across the table between the rows labeled 58 and 72. The last statement in the sublegend, regarding circumference counts, is inapplicable.

three recently collected hybrids the peritoneum is black. In the length and orientation of the gut they are intermediate between the parental species. The double loops of the intestine are mostly diagonal in the ventral aspect of the body cavity, instead of being predominantly transverse as in *Campostoma* or longitudinal as in *Chrosomus*, and the loops fold far up on the sides of the coelom but do not completely envelop the air bladder.

Color pattern.—Coloration provides a critical character for testing the identification of the hybrids, for *C. erythrogaster* is distinctive among Illinois minnows in having two prominent lateral dark stripes, one above and one below the axial septum. In *Campostoma* there is a single faint axial dark band. In the type of *pulverulentum* these stripes have presumably become lost through fading, for the other hybrids have two dark lateral bands. The stripes are in the normal position for *Chrosomus*, but are fainter than in that genus. The small basicaudal spot of *Chrosomus* and the larger dusky blotch on the proximal part of the median caudal rays of *Campostoma* are both evident in the hybrid from Kansas.

Characters of the hybrids.—As emphasized above, almost all characters in the hybrids exhibit intermediacy. For those characters that can be quantified readily the deviation from strict intermediacy may be expressed in absolute meristic units or by a measurement ratio, and percentagewise by hybrid indices. The values thus obtained (Table II) verify the intermediacy of the hybrids, but in most features a definite approach toward one or the other parent species is indicated (in only one character does the value of the hybrid index fall between 37 and 61, though strictly intermediate values would approach 50). The influence of the *Chrosomus* parentage is more evident in the number of gill rakers, that of *Campostoma* in scale size, development of the lateral line, and possibly in anal ray count, but near perfect intermediacy obtains for the position of the dorsal fin.

Averages for each hybrid specimen of the several hybrid indices of the separate characters have values of 46 to 56, with a grand average for the four hybrids of 52. In computing these averages the separate gill-raker counts were included, but the total count was excluded. The counts of pored scales and of unpored scales were also excluded, because the interaction of two independent characters, scale size, and lateral-line development can be shown to yield mean values and hybrid indices that are not intermediate, even though each character itself were strictly intermediate. Grand averages close to 50 have been obtained in other recent studies of natural hybrids, for instance in the Catostomidae (Hubbs, Hubbs, and Johnson, 1943). The analysis of hybridity through the computation of such composite hybrid indices, however, involves very considerable sources of error and subjective selection of characters. The computations are regarded by the senior author as having considerable value, despite their low order of precision; by the junior author, as being too unreliable to warrent inclusion.

ZOOGEOGRAPHICAL AND ECOLOGICAL CONSIDERATIONS

The four hybrids were all taken in the very broad area of overlap between the ranges of the parental species, which often occupy similar types of streams. All were taken where both species are known or may well be presumed to occur. Forbes and Richardson (1909, maps 23 and 24) charted two records for *C. anomalum* along the Illinois River near Peoria (the type locality of *O. pulverulentum*) and several records in this river system for *C. erythrogaster*, including one in a tributary that enters the river near Peoria. Two of the other hybrid specimens were taken in company with both parental species; the Iowa fish was associated with *Campostoma* only, but *Chrosomus* is common nearby.

The parental species both breed on gravel riffles in the spring (Smith, 1908; Hubbs and Cooper, 1936: 88). The senior author has seen both in a swarm of several species of minnows that were breeding together on the same gravel patch. Such spawning situations seem to be responsible for much of the interspecific hybridization in the Cyprinidae.

The hybridity of "*Oxygeneum pulverulentum*" is further attested by its excessive rarity over a broad area, in a region that has been subjected to intensive collecting and study for many years. Even the rarest of the obviously valid species of this region are mostly now represented in collections, particularly in the University of Michigan Museum of Zoology, by dozens of series.

SUMMARY AND CONCLUSIONS

Oxygeneum pulverulentum Forbes, a nominal species of cyprinid fish from Illinois that has defied placement in the systematic structure, proves on a critical study of the type and only previously recorded specimen to be interpretable as a hybrid, *Campostoma anomalum pullum* × *Chrosomus erythrogaster*. This specimen and three others of the same interspecific cross are intermediate in almost all characters, though in most respects the hybrids are somewhat closer to one of the parental species. Thus, in the number of gill rakers, the hybrids are more like the *Chrosomus* than the *Campostoma*, whereas the reverse seems to be true for the scale counts and perhaps for the number of anal rays. Partial dominance may be involved. Completeness of the lateral line appears to be dominant over incompleteness.

When the extreme rarity of this type of minnow is considered, along with the evidence (1) that hybridization is particularly common and widespread among the Cyprinidae, (2) that no obvious ecological barriers to such hybridization are known, and (3) that the specimens have the very characters that one would expect in a hybrid of the indicated combination, confidence in the interpretation becomes virtually complete.

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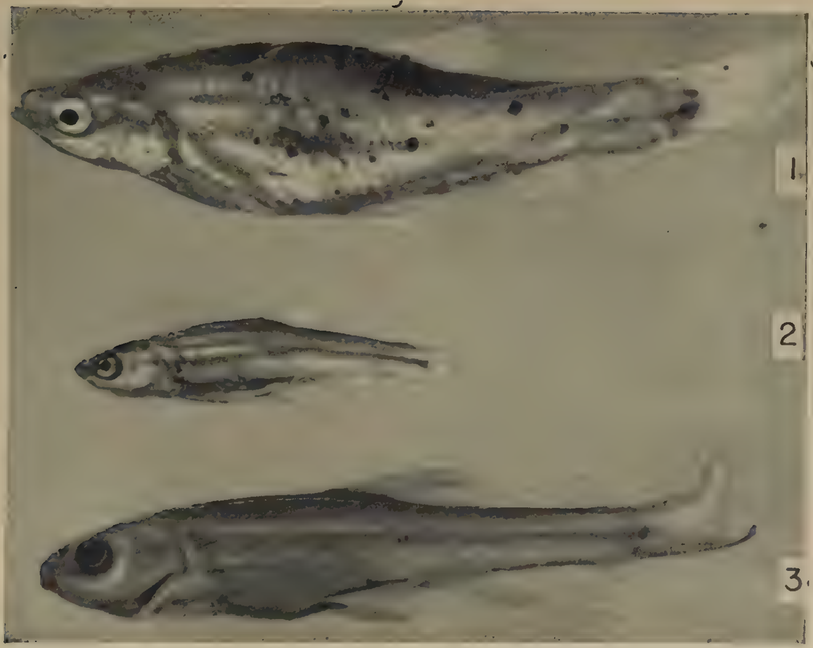

Hybrid cyprinids, *Campostoma anomalum* × *Chrosomus erythrogaster*

FIG. 1. U.M.M.Z. No. 100971, 56 mm. in standard length, from Delaware County, Iowa

FIG. 2. U.M.M.Z. No. 103132, 29 mm. in length, from Delaware County, Oklahoma

FIG. 3. U.M.M.Z. No. 122039, 49 mm. long, from Riley County, Kansas

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HOTOSYNTHESIS, GROWTH AND TRANSLOCATION IN GIANT KELP[1]

Marston C. Sargent and Lester W. Lantrip

s TO BE expected that a plant like the giant
Iacrocystis pyrifera (Turn.) Ag., with mas-
wer parts existing for several years in greatly
d light or utter darkness connected only by
r structures to the rampant crown, should
n efficient system for the translocation of
c matter. Observations on the morphology
ninariales early established the existence of
res suitable for this function. According
es (1908) "J. J. Parker of Otago first no-
stipe elements which were thereafter named
tubes" by Will (1884) who first gave a de-
description. References to the many later
of the morphology of these structures may
d in Fritsch (1945).

ough the conducting function of these ele-
has probably never been seriously doubted,
ts to demonstrate it have been few and the
ons uncertain. Wille (1885)[2] found that
osphorus and nitrogen content of blades of *Laminaria* diminishes before they drop off and suggested that at this time ash components are translocated from older to younger blades. A shadow of doubt has been cast on Wille's suggestion by Bodenberg (1928) who failed to induce translocation of lithium chloride in the stipe of *Nereocystis*. Oltmanns (1923, Vol. 3, p. 207) expressed a generally accepted view, "As the algae are bathed in water on all sides and doubtless can absorb salts over their whole surface, there is no reason to expect abundant translocation of (inorganic) nutrients in the same sense as in higher plants." Although there is no convincing evidence, experimental or logical, against Wille's hypothesis, there seems to be reason to expect considerably larger translocation of organic than of inorganic matter. Skottsberg (1907, p. 134) summed up his experience and opinion in a sentence which covers all our knowledge of this subject to the present time, "Also a great deal of (organic) nutrient is stored in the haptera which probably is not merely formed through the activity of the haptera but is also translocated to them."

The observations described in this report are in accord with Skottsberg's conjecture and, we believe,

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eived for publication June 20, 1951.
ibutions from the Scripps Institution of Ocean-
, New Series, No. 556.
have not seen this reference. It is quoted in
1889).

reveal other interesting aspects of the translocation system of the giant kelp.

METHODS.—A buoy was constructed of two 5-gal. drums secured to the ends of two parallel 1 in. angle irons 6 ft. long. A piece of ½ in. mesh hardware cloth was bent over the angle irons into a trough of square cross-section, with closed ends, big enough to hold two layers of bottles laid horizontally, side by side. A flat piece of hardware cloth secured with short pieces of baling wire covered the open top of the box. The top of the upper layer of bottles floated 5 or 10 cm. below the surface. The buoy was moored with a 6 lb. anchor.

A punch, made by sharpening one end of a piece of stainless steel tubing 7/16 in. inside diameter was used to punch out 0.95 cm.^{2} pieces of kelp blade.

For each experiment 5-gal. of sea water collected beforehand were filtered through paper and sintered glass to remove essentially all organisms above the size of bacteria. This water was stored in the dark for several days or a week before use, and had a relatively low oxygen content at the beginning of the experiment.

The experiment began as soon after daylight as it was possible to select suitable material. When a suitable frond was located, the whole surface portion, often a length of 10 m. or more, was broken off and brought aboard. Beginning at the tip of the frond selected, the blades were counted and the stipe length measured. At intervals, beginning with the first separate blade after the compound terminal blade, a blade was removed for experiment. Near the tip where the blades were small, several adjacent ones were often collected and farther down the stipe approximately every tenth to twentieth blade, in each case taking care that the blade removed was typical of its neighbors. The lowest blade selected was ordinarily moderately overgrown with sessile animals and small algae. Some experiments were designed also to make measurements on pieces of stipe. In each case, the whole blade with attached float, pedicel and stipe internode down to the insertion of the next pedicel was taken. Four 0.95 cm.^{2} pieces were punched out of each selected blade and washed free of exuded laminarin in freshly drawn sea water. Two pieces were put in each of two numbered 550 ml. glass stoppered pyrex bottles completely filled by siphoning from the 5 gal. reservoir of filtered water. Each bottle contained two glass marbles to act as stirrers while it was afloat.

Two bottles received no kelp and served to measure the activity of microorganisms in the water. As soon as all the bottles were full, one of each pair was wrapped in black cloth, and laid in the buoy. The unwrapped bottles were laid on top, the cover secured and the buoy sent over the side at a position previously selected in a clearing in the kelp bed which could be located by ranges on shore.

This work was ordinarily accomplished by, shortly after, sunrise. Immediately afterwa water samples from the reservoir were fixed v Winkler reagents. The selected blades were turned to the laboratory for measurement, dry and weighing.

As close as possible to noon, the buoy brought aboard. There are several reasons restricting experiments to a duration of only ab 6 hr. We presume that the degenerative eff of excising the tissue become more pronour with the passage of time. The bacterial popula and consequently the rate of bacterial activity creases. The weather may change and the b and samples be lost. We assume that the cha from sunrise to noon can be multiplied by give the change from sunrise to sunset and change in a dark bottle can be multiplied by give very nearly the change in 24 hr.

As soon as the buoy was aboard, the pieces tissue were removed and the water samples fi with Winkler reagents. Occasionally a bottle tained a gas bubble when removed from the bu If so, the contents were discarded.

Tracings of the selected blades were measu with a planimeter. The blades were then freed encrusting organisms by careful brushing, rubb and scraping, and inserted in weighed flasks. were dried to constant weight at 130°C. The gen content of the water in the bottles was measu by Winkler titration.

Three criteria that obviously must be met experiments of this kind are that (a) the temp tures in the experimental bottles shall be practi ly the same as the external temperature; (b) light intensity shall be effectively the same as to which the intact plant is exposed; (c) the ch ical resources of the enclosed sample of water not be utilized to such an extent that the acti of the tissue is diminished.

In our experiments these criteria were met to following extent. (a) The temperature inside the tles was less than 0.1 °C. different from the ave of that outside. The moment to moment variat in the temperature of the outside water were la than this. (b) The light intensity was diminis to the extent that the hardware cloth and o parts of the buoy assembly subtended upward 10 per cent of the solid angle around the ce of each experimental bottle. Tseng in unpublis work has shown that, as in many other plants, tosynthesis in *Macrocystis* is independent of intensity above intensities of about one-tenth that of bright, noonday, sunlight. Over a pe of half a day the effect of shading should be siderably less percentagewise than the amoun shading. (c) The length of time that an encl sample of water can support an uninhibited of photosynthesis has usually been considered limited by the amount of available carbon dio Emerson and Green (1934) and Tseng

ney (1946) have worked on the practical so-
. of this problem for measurements of photo-
esis in sea water. We have not followed
authors in adding carbon dioxide to the sea
but have utilized large water volume to sam-
olume ratios (about 100–200 times as large
herson and Green's and about 10 times as large
eng and Sweeney's) and provided for moder-
active stirring. In our experiments the most
blades had a rate of photosynthesis close to,
omewhat less than, the rates observed by
(unpublished data) in laboratory experi-
at saturating light intensities, enhanced car-
lioxide concentrations and the same tempera-
(19–21°C.).

BIT OF THE GIANT KELP.—The general habit
acroystis pyrifera is familiar, to many who
never seen it, through descriptions in standard
such as Fritsch (1945). The pyramidal or
l holdfast of densely intertwining and free-
nching haptera is often a meter or more in
ter and sometimes approaches a meter in
. From it arise by basal branching several
which may become more than 40 m. long.
ature plants, a multitude of short branches
clothed with relatively delicate sporophyl-
lades occur at the base. Along the vegetative
branches, blades are borne in a double rank,
rly spaced from top to bottom. Large blades
a length of a meter or more and a width of
. but are only 0.5–3 mm. thick; the smallest
e blades are seldom less than 0.5 m. long.
ase of each blade is expanded into a pear
l (in some plants spherical) float a few cen-
rs long which narrows to a cylindrical pedi-
ining the blade to the stipe. The length of
pe internode between pedicels increases from
g at the growing tip to 0.4 m. or more near
se of an old stipe.

e details of the habit can best be illustrated
ures and tables of measurements. In a large,
y growing, frond, the broad scimitar-shaped
al blade splits in such a way that ribbon-
l segments ultimately tear away from its
edge and become independent blades. As
l shows, in any plant in active growth the
the blades increases with increasing distance
he growing tip up to a maximum size. Be-
his point in many plants, sloughing of the
tips, general decay of the blades, growth of
ed organisms or other evidence of age make
rements impossible or meaningless. However,
plant where such conditions do not hamper
ation, it is possible to demonstrate that in-
in size of blades with increasing distance
he tip finally ceases. Beyond this point on
pe, the largest blades are either no larger
ne largest ones above, or even smaller.

criterion of growth in these plants most
apprehended by the eye is either blade area
de length. More generally acceptable parameters are wet weight and dry weight. Table 1 shows that the dry weight of individual blades also reaches a maximum value. The dry weight of each blade and of the associated float, pedicel and stipe internode is plotted in fig. 1, which shows that the dry weight of the floats, pedicels and stipe internodes also reaches very nearly its maximum value relatively close to the growing tip, and beyond that changes little.

TABLE 1. *Areas and dry weights of blades of Macrocystis.*

Blade number[a]	Area cm.^{2}	Dry weight g.	Dry weight per unit area g./cm.^{2}
16	47	0.33	6.9×10^{-3}
31	142	1.01	7.1
41	207	1.62	7.8
50	244	2.07	8.5
70	239	2.52	10.5
93	229	2.69	11.7
110	276	3.25	11.7
132	313	3.21	10.2
151	368	3.65	9.9

[a] Blade number one is the first clearly marked off segment in the terminal blade.

Another quantity that would be of interest is the total organic matter per blade, float and stipe. This we have not measured. However, Hoagland (1915) has shown that in harvestable portions of the plant

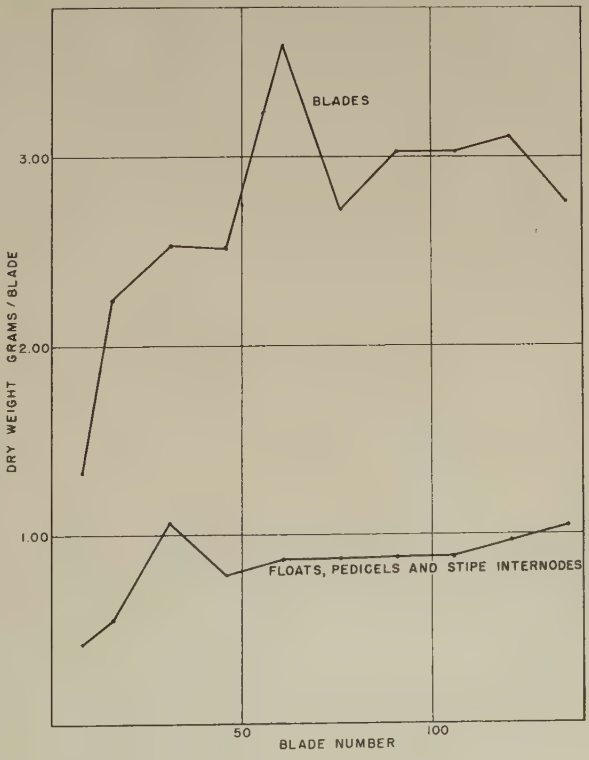

Fig. 1. Dry weight of individual blades and of associated floats, pedicels and stipe internodes of *Macrocystis.*

(that is, portions growing near the surface), organic matter constituted, on the average, 64.5 per cent of the dry weight of blades and 54.9 per cent of the dry weight of stipes. Observations of Turrentine (1912) are in close agreement. We have adopted the convention that it constitutes 65 per cent of the dry weight of all parts of the plant we are working with. Fig. 2 shows the total weight of organic matter computed on this basis in each combined blade, float, pedicel and stipe internode measured.

Table 2 shows the distribution of mass in a whole plant collected by a diver in about 8 m. of water. It was brought ashore, stretched out with all the branches lying together in a bundle more or less parallel, measured and cut into 3-ft. bundles which were weighed individually. All pebbles and other large foreign objects were carefully picked out of the holdfast, and, as far as reasonably possible, smaller material was scraped or broken off. It is, of course prohibitively difficult to get a large holdfast clean, but the mass of foreign material weighed in with this specimen was a negligible fraction of the mass of holdfast tissue which broke off during the collection or had previously decayed. The mass of the upper 9 yd. of the plant was about equal to that of the lower 9 yd., but most of the mass of the latter was concentrated in the holdfast and sporophylls. The numerous short vegetative branches were sparsely covered with blades, largely because the blades were farther apart on the stipe, and the longer branches were bare on their basal parts both for this reason and also because blades had rotted away. The portions of branches lying at the surface were on the whole thickly covered with large healthy blades.

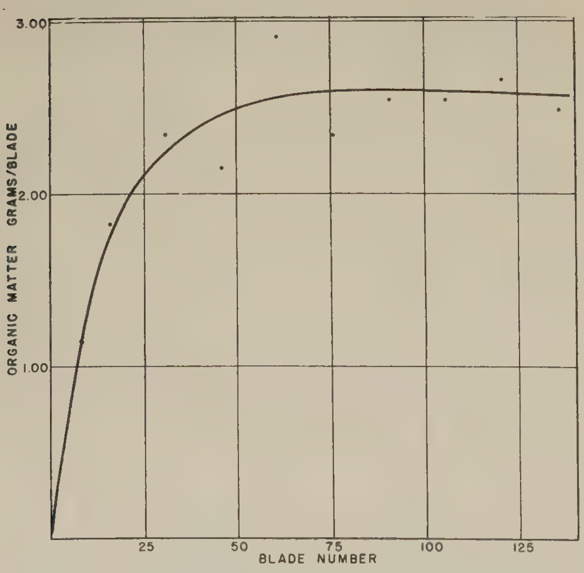

Fig. 2. Organic matter in individual blades including associated floats, pedicels and stipe internodes.

TABLE 2. *Distribution of mass in a fresh Macrocystis pl*
Each section 3 ft. long.

Section number	Wet weight kg.
1[a]	0.74
2	1.02
3	1.36
4	1.58
5	3.17
6	1.92
7	1.36
8	1.36
9	1.47
10	1.24
11	1.02
12	0.91
13	0.91
14	1.02
15	1.24
16	1.02
17	1.13
sporophylls	3.51
holdfast	5.11

[a] Section number one includes the growing tips of four longest frond branches.

A whole plant six times as heavy as this recorded by Burd (1915), and general experi indicates that this specimen is of modest size. differs from Burd's three specimens, all of t larger, principally in that the holdfast repres only about 16 per cent of the total weight, whil the other plants it represented 30–35 per cent o total. This is a very small sample to gener from, but we may guess that as *Macrocystis* short lived perennial whose top is often hea pruned by winter storms, it will continually b up a larger and larger holdfast, while its mas crown averaged over the year may, after the few years, increase little from year to year.

GROWTH RATE.—The quantitative represent of the habit of the kelp plant in fig. 2 is evid some kind of an expression of the variation in of the size of the individual blade with its ciated float and portion of stipe. If the relatio the scale of leaf position to a time scale known, the curve in fig. 2 would be the gr curve for an individual blade. In particula the date of formation of each blade could b tablished, this would be true. It has not s proved possible to make satisfactory observa on this point. As the observations reported were made in August, we can assume that d the 40–60 days since the solstice, growing c tions had been reasonably constant, and the of blade formation could likewise be ass reasonably constant throughout that period, s the relation between the position scale and the scale would be linear.

Mr. Charles Martin of the Kelco Compan

y permitted the use of his extensive observa- on the rate of elongation of kelp fronds. observations were made by cutting off frond f various lengths, measuring them, securing to a buoy and measuring them again after terval of several days. Forty-three determi- ns in June, July and August gave an average f elongation of 7.1 cm. a day with a standard ion of ± 4.3 cm. Our own observations that the length of an internode increases y in the first meter from the tip, but much slowly thereafter throughout the remainder of rtion of the stipe which floats at the surface. ding the values in the first meter and the for the upright portion of the stipe, the ge length of an internode is 5.7 ± 0.6 cm. the basis of these values the average rate of tion of blades during the weeks just pre- our observation was at least 1.25 blades . Reasons appear below for believing that a minimum estimate. If these assumptions rrect, the values on the abscissa of fig. 2 can ltiplied by 0.8 to convert it to a scale of time s. Without further transformation the curve hows the amount of organic matter in a blade ry moment since its formation. The slope point is the rate of growth (in grams of or- matter per day) when the blade was at the days shown on the transformed abscissa. rmore, the slope at any blade is the rate of h of that blade on the day our observations made. In order to obtain usable values of pe and to give a more representative picture growth process than the data from a single afford, we have drawn a smooth curve by rough the points in fig. 2.

E OF PHOTOSYNTHESIS.—Fig. 3 shows the of photosynthesis of tissue from the same whose areas and dry weights furnished the for preceding sections. The rate of photo- sis of blades near the tip of the frond is con- bly less than that of blades some distance the stipe. Still farther down, the blades are tive, so that there is a region of the frond the rate of photosynthesis per unit area is aximum. This syndrome is much like that ed in seed plants by Willstätter and Stoll r, 1926, p. 147–149). In deciduous trees rubs, the specific rate of photosynthesis in ing leaves increases rapidly during the first r 10 days and then gradually diminishes. In *cystis* the rate of photosynthesis is low in wly separated blade, increases for several to a maximum rate which is maintained for weeks and then declines. The maximum of photosynthesis observed were somewhat r than those found by Tseng in *Macrocystis* oratory experiments and somewhat larger hose found by Gail (1922) and Tschudy) in *Nereocystis* under "natural" conditions. units in fig. 3 are derived by means of additional experimental data and several assumptions as shown in table 3. Volumes of oxygen have been converted into masses of dextrose on the assumption that the plant produces and consumes oxygen only by the reversible process:

$$6CO_2 + 6H_2O \rightleftharpoons C_6H_{12}O_6 + 6O_2$$

As we are assuming this for tissues of all ages, the corollary assumption is that the plant has the same elementary composition as a carbohydrate. The evidence that this assumption is practically correct is (1) the numerous analyses of Hoagland (1915) indicated that about 60 per cent of the organic matter of *Macrocystis* is carbohydrate and that less than 1 per cent is lipid; (2) an analysis by Spoehr and Milner (1949) gave an R– value of 34 which is consistent with such a composition. As the organic matter of the plant is likely to contain relatively less, rather than more oxygen than does dextrose, the production of a given amount of oxygen probably corresponds to a smaller rate of formation of organic matter than fig. 3 shows. That is, our computed rates of formation of organic matter may be too high.

In fig. 3, areas of blade have been converted into masses of organic matter. We measured directly the dry weight of our material and calculated the corresponding organic matter as described in the last section. We have assumed that the rate of photosynthesis per unit mass of organic matter is the same in float, pedicel and stipe tissue as in the adjacent blade. Because of the relatively large amount of poorly pigmented tissue in these massive structures, it is probably lower, and for this reason also our computed rates may be somewhat too high. As the mass of the blade averages three times as much as the mass of the adjacent structures (fig. 1), the error introduced by the assumption cannot be large.

A third assumption lies behind fig. 3, namely that half of the experimentally observed oxygen

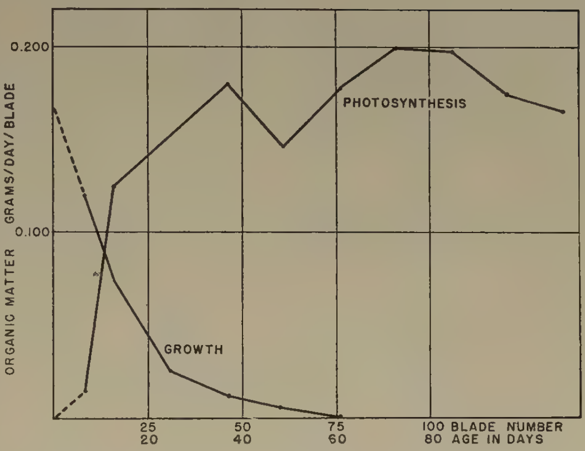

Fig. 3. Rate of photosynthesis and rate of growth of individual blades and associated organs.

TABLE 3. *Export of organic matter from blades of Macrocystis.*

Blade number	Oxygen produced in light bottle by 2 cm.^{2} tissue in 6 hr. ml.	Oxygen consumed in dark bottle by 2 cm.^{2} tissue in 6 hr. ml.	Ratio of dry weight to area of blade g./cm.^{2}	Net photosynthesis of 1 g. (dry) of blade ml./24 hr.	Dry weight of blade g.	Dry weight of float, pedicel and stipe internode g.	Net photosynthesis calculated as $C_6H_{12}O_6$ g./24 hr.	Organic matter in blade, float, pedicel and stipe internode g.	Rate of increase of organic matter g./day	Rate of export of organic matter g./day
8	0.06	0.06	9.77×10^{-2}	6.2	1.32	0.42	14×10^{-3}	1.13	121×10^{-3}	-110×10^{-3}
16	0.33	−0.02	9.82	33.6	2.24	0.55	125	1.81	74	+ 51
31		0.05	10.69		2.53	1.06		2.33	25	
46	0.42	0.06	10.34	40.7	2.51	0.78	180	2.14	12	170
61	0.35	0.05	14.44	24.3	3.60	0.87	146	2.91	5.4	140
76	0.36	0.09	9.72	37.0	2.72	0.87	178	2.33	0	180
91	0.38	0.05	10.03	37.9	3.03	0.88	199	2.54	0	200
106	0.35	0.05	9.33	37.5	3.03	0.88	197	2.54	0	200
121	0.30	0.05	9.44	31.8	3.11	0.96	174	2.64	0	170
136	0.30		9.27	32.4	2.76	1.04	165	2.47	0	160
mean	0.35[a]	0.05	10.29	34.4[a]			170[a]			

[a] Omitting value for blade No. 8.

consumption in the dark bottles is due to resp tion by contaminating bacteria, etc. Table 3 sh that the ratio of respiration to gross photosyn sis is high, about 12 per cent. This is not inher ly incredible but it is almost certain that a con erable part of the observed oxygen consump is due to bacterial oxidation of laminarin copio exuded by the freshly cut kelp tissue during experiment. Even though the pieces were thoro ly washed at the beginning of the experiment the end when they were removed, they trailed dent streamers of a characteristic mucilagi consistency.

Measurements lasting only 1 or 2 hr. on l pieces of holdfast tissue which do not exude se tion in any quantity, showed that under condit minimizing bacterial activity, the rate of resp tion was 38 × 10^{-3} ml. of oxygen/g. of f tissue/hr. Using our value of 0.19 for the rati dry weight to fresh weight, this amounts to 0.2 /g. dry weight/hr., while the average respiratio table 3 recalculated on this basis is 0.41 ml./g. weight/hr. There is no compelling reason to lieve that the rate of respiration of holdfast ti is the same as that of frond tissue; however have somewhat arbitrarily assumed that the fr respiration is about half of the measured ox consumption in the dark bottles. As respira goes on for 24 hr. while photosynthesis only the net daily photosynthesis is considered equ twice the amount of oxygen produced in the bottles. As the respiration may be somewhat h er than we have assumed, the net photosynth may be somewhat lower.

The least net photosynthesis that could be rived from our measurements by a reasonabl of assumptions would have a value at least 75 cent of the one we are using. This is based o following assumption:

1. An increase of 5 per cent in the rati oxygen evolved to organic matter formed w correspond to replacing nearly 8 per cent o ganic matter having an average elementary co sition like that of glucose, with organic m having an average elementary composition like of a fat. As *Macrocystis* contains far less than this, it is likely that the rate of produ of organic matter is at least 95 per cent o rate according to our original assumption.

2. The rate of photosynthesis of float, pe and stipe tissue per unit dry weight might be one half that of blade tissue. These tissue gether weigh less than one-third as much a adjacent blade. The rate of photosynthesis o whole assembly would then be reduced by no than one-half of 24 per cent, or to 88 per ce our assumed rate.

3. The rate of respiration of the most a photosynthetic tissues might be as much as 1 cent of the gross rate of photosynthesis. A

een assuming that the respiratory rate equals 6 per cent of the photosynthesis, the true net f photosynthesis might be (taking into ac- the respiration at night) only 91 per cent of alue given.

final result is that using the most belittling ptions that are reasonable, the net photosyn- would be in any case more than 75 per cent t shown. We believe that the most probable lies on the average, somewhere between 80– r cent of the values shown in our tables and s. It is very unlikely that the rate of photo- esis is larger than we have assumed in our ations.

ORT AND TRANSLOCATION OF ORGANIC MATTER. fig. 3, along with the data on rate of photo- esis, is plotted the rate of growth obtained by ring graphically the slope of the smoothed in fig. 2 at a suitable number of points. Both se curves show for each blade on the day on the observations were made the rates of h and of photosynthesis in the same units: of organic matter per day. It is therefore le on any ordinate to subtract the value of nction from the value of the other and obtain sult: Rate of photosynthesis minus rate of h equals rate of export.

amount of organic matter exported from lade equals the amount synthesized less the t used in growth by that blade. If the amount n growth exceeds the amount synthesized, or- matter must be imported.

ppears at once, as shown in fig. 4, that the f export is not in general zero. Most blades porting organic matter at a considerable rate me may be importing it. In particular, it ar that over a considerable length of the at all blade numbers larger than about 50, te of growth is extremely small and the rate tosynthesis is large, and consequently so is te of export.

n fig. 4 it appears that the average rate of per blade from blade 37 to blade 136 (for ience) is about 0.2 g. of organic matter per The total amount for all 100 blades is then 20 day. There are several imaginable fates for s of this organic matter. The least attrac- e is that some of the material is exported he plant entirely, for example by secretion inarin into the surrounding water as sug- by Skottsberg (1907, p. 136). The kelps do generate excised tissue, so that we can not e that organic matter is continually removed zers and replaced by regeneration. A more tory possibility is that some is translocated ther part of the plant where growth or ac- tion in storage tissues is greater than pho- esis, for instance the holdfast. A very real lity is that parts of the holdfast which are and not carrying on photosynthesis, require ation of organic matter to support respiration. It is quite likely that several if not all of these processes are going on simultaneously.

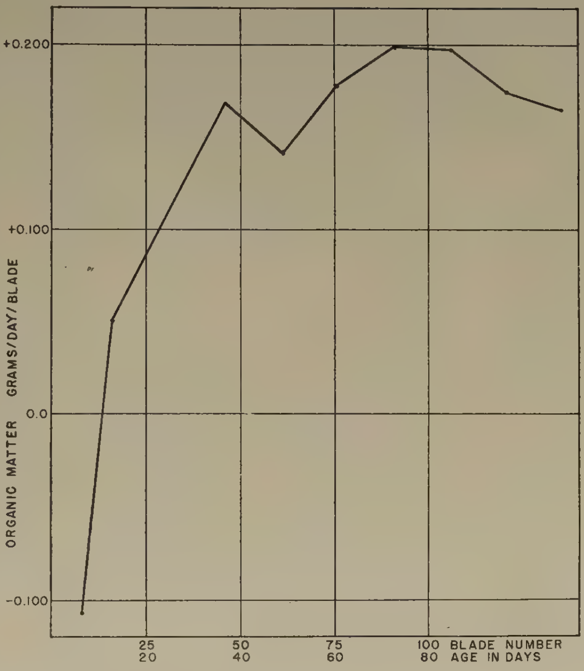

Fig. 4. Rate of export of organic matter from individual blades and associated organs.

Fig. 4 shows one clean cut use for exported organic matter. In this plant all the blades up to about number 13 were importing organic matter. Table 4, describing the only other plants studied completely enough to furnish evidence on this point, shows that the phenomenon is general. The growing tip of *Macrocystis* grows at a rate which exceeds its rate of photosynthesis and must import organic matter from lower blades on the frond. A rough integration of the portion of the curve below zero in fig. 4 indicates that the amount of organic matter imported by the growing tip was equal to that exported by the rest of the frond as far as about blade 35. Approximately 2 g. of organic matter a day was translocated toward the growing tip through the stipe at about blade 13.

Comparison of the integrals of the two curves in fig. 3 shows that about one sixth of the photosynthetic product of the piece of frond studied was being used for the overall production of new tissue in the same frond. We suspect, however, a considerably larger growth rate than available observations indicate, and consequently a smaller excess of photosynthetic product than fig. 3 shows. The remainder must be translocated downward for some of the purposes already named, or removed from the crown by some other mechanism. To account for this remainder, we have attempted to calculate the budget of the entire plant described in table 2. This calculation, shown in table 5, uses mostly data

TABLE 4. *Rates of photosynthesis, growth and export of organic matter in blades of Macrocystis.*

Plant collected 2 Aug.				Plant collected 9 Aug.			
Blade No.	Rate of photosynthesis mg./day	Rate of growth mg./day	Rate of export mg./day	Blade No.	Rate of photosynthesis mg./day	Rate of growth mg./day	Rate of export mg./day
16	13	39	−26	15	7.5	17	−10
23	21	33	−12	31	55	55	0
30	74	28	+46	42	173	60	+110
41	156	24	130	52	229	60	170
50	223	20	200	62	244	60	180
70	238	18	220	72	330	0	330
93	200	12	190	82	318	−3.5	320
110	240	10	230	92	310	−3.5	310
132	272	6	270				
151	262	3	260				

already given, and is based on two major assumptions:

(1) The upper half (by weight) of the plant collected, which lay just under the surface and carried most of the blades, performed photosynthesis at a uniform rate; (2) the lower half of the plant did no photosynthesis and carried on respiration at a uniform rate.

The average net rate of photosynthesis appears in table 3. The average rate of respiration of holdfast tissue was independently determined and has been quoted above. The ratio of dry weight to wet weight of blades, independently determined, is higher than Hoagland's (1915) value of 0.15, but this makes a difference of only about 5 per cent in the final result. The ratio of dry weight to organic matter is mentioned above.

It appears from the calculation that a relatively small amount of the total production of organic matter is required to support the respiration of the submerged parts. (The respiration of the crown has been excluded from the calculation by the use of net photosynthesis.) The amount used in growth of haptera is also small as shown by the fact that the largest holdfast recorded (Burd, 1915) weighed 62 kg. and was presumed to be 6–8 years old. A relatively small rate of supply of organic matter would account for development of the cluster of sporophylls in a few months. We are driven to
the conclusion that the greatest part of the ex
of photosynthesis over respiration shown in t
5, unless it is escaping from the plants, is accu
lating as storage material in the haptera in acc
ance with Skottsberg's suggestion, quoted p
ously.

The ultimate fate of a large part of such st
material is suggested by our observation that g
ing tips must import organic matter. At all
sons of the year, there is a certain amount of
pruning by weather and accident, and winter st
prune the plants heavily. If growing tips
under summer conditions at the surface ca
meet their own demands for organic matter,
growth starting close to the bottom under late
ter conditions of low sun and high turbidity
need to import organic matter until they are
to the surface. Brandt's (1923, p. 9) observat
indicate that winter growth may be very was
in that fronds are repeatedly pruned while or
few feet long. Under such conditions large amo
of material may be withdrawn from the hap
before any growing tips reach and remain or
surface long enough to start repaying the debt.

SUMMARY

From simultaneous measurements of phot
thesis and growth rate of the giant kelp, *M
cystis pyrifera*, it can be inferred that there is

TABLE 5. *Budget of a Macrocystis plant.*

Wet weight of crown (sections 1–10 in table 2)	15.2 × 10^3 g.
Ratio of dry weight to wet weight (independent determination)	0.19 g./g.
Dry weight of crown	2.89 × 10^3 g.
Average net rate of photosynthesis (from table 3)	34.4 ml. O_2/g. dry weight/
Total net photosynthesis	99.6 × 10^3 ml. O_2/day
Wet weight of submerged parts (sections 11–17 plus sporophylls and holdfast in table 2)	15.9 × 10^3 g.
Average rate of respiration (independent determination)	0.92 ml. O_2/g. wet weight/
Total respiration	14.6 × 10^3 ml. O_2/day
Excess of photosynthesis over respiration	85 × 10^3 ml. O_2/day
Ratio of $C_6H_{12}O_6$ to O_2	1.34 × 10^{-3} g./ml.
Ratio of dry weight to organic matter (from Hoagland)	1.55 g./g.
Ratio of wet weight to dry weight (independent determination)	5.28 g./g.
Total wet tissue production	940 g./day

anslocation of organic matter through the The daily increase in dry weight of blades at of an actively growing frond is greater e daily product of their own photosynthesis. te of photosynthesis of blades farther down e greatly exceeds their rate of growth. Up- ranslocation of organic matter in the upper of the frond is required to balance the bud- he daily rate of production of organic matter in summer by a whole frond greatly exceeds its rate of growth. Downward translocation to supply material for growth of the holdfast and other deeply submerged organs, to supply their current needs for respiration and to supply storage material for spring growth is inferred.

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OOLOGY.—*Geographical distribution of the species of nemerteans of the Arctic Ocean near Point Barrow, Alaska.*[1] WESLEY R. COE, Scripps Institution of Oceanography. (Communicated by Fenner A. Chace, Jr.)

Nemerteans occur along the borders of all e oceans, from beneath the Polar Seas rthwest of Greenland (Coe, 1944) to the barrier surrounding the South Pole oe, 1950). Moreover most of the same nera, but not the same species, are found both these extremes of latitude.

The floor of the Arctic Ocean near Point arrow is evidently well adapted for popu- tions of nemerteans, for Prof. and Mrs. eorge MacGinitie during their two years the Arctic Research Laboratory[2] collected ore than 300 specimens of these worms. emerteans were found at nearly all the edging stations, from shallow water to ths of about 250 meters 12 to 16 miles m shore. The collections contained 24 cognizable species, among which are 7 ecies of *Amphiporus*, 4 of *Tubulanus*, 3 of *Micrura*, 4 of *Tetrastemma*, 2 of *Cerebratulus*, 1 each of *Lineus*, *Emplectonema*, *Nemertopsis*, and *Paranemertes*. As in other collections from Arctic seas, the genus *Amphiporus* has not only the greatest number of species but some of the species have also the largest populations. *A. angulatus* and *A. lactifloreus* are the most abundant species in the Point Barrow area. Ten of the species have not been reported previously from strictly Arctic seas, although three of these have been found in the nearby Bering Sea.

These collections are of particular interest because only three species of nemerteans were formerly known from that portion of the Arctic seas and the others contribute to an understanding of the circumpolar distribution of some of the species. Even at the present time no nemerteans are known from the Polar seas between the Point Barrow area and northwest Greenland on the east and Nova Zemblya and Franz Josef Land on the west.

From the Polar seas the populations of

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[1] Contribution of the Scripps Institution of eanography, new series, no. 557.

[2] Supported by the Office of Naval Research ough contracts with the California Institute Technology and the Johns Hopkins University.

several of the species extend southward along the European, American, and Asiatic coasts. *Cerebratulus marginatus* may be mentioned as a species with an unusually extensive geographical distribution, for the range of this species extends from near King Karl Land, Spitsbergen, and elsewhere in the Arctic to Norway, Great Britain, the Mediterranean and Madeira in the eastern Atlantic and from Greenland to Labrador, Nova Scotia, New England, Cape Cod, and farther southward beneath the offshore current in the western Atlantic. It also extends from the Point Barrow area, Bering Sea, Pacific coast of Alaska and southward to southern California along the American coast, and to Kamchatka and Japan on the Asiatic coast. This does not imply that the populations in the present geological era are continuous through all this vast extent of territory, nor can it be assumed that the species originated in that portion of the globe which is now occupied by the Polar seas. The species presumably exists as isolated, localized, more or less widely separated populations. Moreover it is probable that it is even more widely distributed than is at present known.

Four other species, *Lineus ruber*, *Cerebratulus fuscus*, *Amphiporus lactifloreus*, and *Tetrastemma candidum*, similarly extend southward along the European and American Atlantic coasts, while *Amphiporus angulatus* extends from Greenland as far south as southern New England in the western Atlantic and from Point Barrow to California on the American coast, as well as to Japan on the Asiatic coast, but it has not been found in the eastern Atlantic.

Amphiporus lactifloreus occurs on both the European and American Atlantic coasts, as well as in the Arctic, but has not been reported from the Pacific, while *Tubulanus capistratus* is found on both sides of the Pacific, from Point Barrow to California and to Japan, but not in the Atlantic. The Point Barrow area therefore forms an intermediate link for those species formerly known to occur in the Polar seas north of Europe or near the coasts of Greenland, or both, and those on either the American or Asiatic Pacific coasts or both.

Relatively few species of nemerteans are known to occur in both the Northern and Southern Hemispheres. Of those here reported for the Point Barrow area, *Tubulanus annulatus*, *Lineus ruber*, *Cerebratulus fuscus*, and *Tetrastemma candidum* have been found also on the coast of South Africa and *Emplectonema gracile* on the coast of Chile.

The following list, arranged in systematic order, gives the geographical distribution of each of the species found in the Point Barrow area in so far as at present known. A similar list of the distribution of other species reported for Arctic seas has been published by Coe (1944).

Order PALEONEMERTEA

Tubulanus albocinctus (Coe), 1904. This is the first record of this species in Arctic seas. It has been dredged previously among red algae at depths of 100 to 200 meters off the coast of southern California. One specimen, about 107 mm in length, was collected at a depth of 65 meters between 4 and 5 miles from shore off Point Barrow.

Tubulanus annulatus (Montagu), 1804. This species is widely distributed on the eastern shores of the North Atlantic, from Norway and Great Britain to the Mediterranean; it has also been reported from the South Atlantic, near the Cape of Good Hope. In the Arctic it has been dredged near King Karl Land, off Cape Platen, and in the Karajek Fiord, Greenland, as well as off the northwest coast of Greenland (Coe, 1944). In the Point Barrow area it was found at depths up to 126 meters and up to 7 miles from shore.

Tubulanus capistratus (Coe), 1901. This species is closely similar to the preceding but is without the white band on the dorsal surface of the head. It has been found in the intertidal zone and below along the Pacific coast of Alaska and southward to Monterey Bay, Calif., and it is also reported from Japan. In the Point Barrow area it was collected at depths of 3 and 131 meters, from near shore and 12 miles out.

Tubulanus frenatus (Coe), 1904. One specimen was found near Point Barrow. Previously recorded only from southern California.

Order HETERONEMERTEA

Lineus ruber (O. F. Müller), 1771. Circumpolar coasts of Siberia; Greenland; Norway and Grea Britain to the Mediterranean, Madeira and Sout Africa; Labrador to southern New England aska to California. In the collections from the oint Barrow area only two specimens were assgned to this species. One of these was found near ore and the other ot a depth of 136 meters 8 iles out.

Micrura alaskensis Coe, 1901. A common ecies in the intertidal zone and below along the acific coast of Alaska and southward to northern exico. Found also in Japan. In the Point Barw area only four individuals were obtained. One these was found near shore and the others 4 to miles out, at depths of 50 to 65 meters.

Micrura impressa (Stimpson), 1857. Originally scribed from an individual dredged in Bering rait. Later reported from Japan (Yamaoka, 40). One specimen measuring 97 mm in length d 9 mm in width when contracted was found ashed ashore at Point Barrow.

Micrura purpurea (Dalyell), 1853. Reported in rctic seas northwest of Greenland, Karajak ord and Hinlopen Strait at depths of 45 to 115 eters (Coe, 1944). Common on European coasts om the intertidal zone to depths of 200 meters more. One specimen was obtained in the Point arrow area at a depth of 143 meters, 16 miles om shore.

(*Cerebratulus barentsi* Bürger, 1895. The minor orphological features which have been thought separate this species from *C. marginatus* have idently resulted from different states of conaction of the head. Hence *C. barentsi* is no nger considered to be a valid species.)

Cerebratulus fuscus (McIntosh), 1873–4. This a species with a very wide geographical distriıtion, for it has been reported not only from the asts of Greenland and elsewhere in Arctic seas, t also from Norway and Great Britain to the editerranean, as well as South Africa and orida (Coe, 1951). The single specimen colted in the Point Barrow area was dredged at a pth of 41 meters, 3.5 miles from shore.

Cerebratulus marginatus Renier, 1804. This ecies has the wide circumpolar distribution eviously mentioned, being found on European asts as far south as Madeira; on the eastern rth American coasts it extends southward to pe Cod and farther south beneath the offshore rrent; on the western North American coast ıthward to southern California and in the stern Pacific as far south as Japan. In the ctic it has been reported from King Karl Land, emer Sound, Hinlopen Strait, East Spisbergen, d northwest Greenland. In the Point Barrow area it was found at depths of 61 to 222 meters, 5 to 12 miles from shore.

Order Hoplonemertea

Emplectonema gracile (Johnston), 1837. One small specimen about 30 mm long and 1 to 2 mm in diameter after preservation was obtained in the Point Barrow area at a depth of 38 meters. This is one of the most widely distributed of all species of nemerteans, being abundant in the intertidal zone and below, on the northern coasts of Europe and southward to Madeira; on the coasts of Alaska to California and northern Mexico, and it has been reported also from Chile, as well as from Kamchatka and Japan. It has not been recorded previously from Arctic areas.

Paranemertes peregrina Coe, 1901. In many localities this is the most abundant nemertean in the intertidal zone along the Pacific coast of Alaska and southward to California. It has also been reported from the Aleutian Islands, Kamchatka and Japan. Only a single representative of this species was found in the Point Barrow area.

Nemertopsis gracilis Coe, 1904. Previously reported from Pugent Sound to northern Mexico. Only one specimen was dredged in the Point Barrow area.

Amphiporus angulatus (Fabricius), 1774. The collections indicate that this is the most abundant nemertean in the Point Barrow region. Because of the relatively large size of many individuals and their conspicuous coloration, it is unlikely that they would be overlooked by the collector. This species was found at 9 stations, where the depths were between 12 and 226 meters. The distance from shore varied from 2.75 to 16 miles. This species is widely distributed in Arctic seas, having been reported from near Greenland, Baffin Bay, Davis Strait, Labrador, Nova Scotia, southward to Cape Cod and further south beneath the offshore Arctic current. On the Pacific coast of North America it extends through Bering Sea, along the coast of Alaska and south as far as Point Conception, California. On the Asiatic coast it has been found on the shores of Kamchatka and Japan. It was collected by Stimpson (1857) in Bering Strait.

Amphiporus formidabilis Griffin, 1898. Previously recorded from Bering Island, Aleutian Islands, coast of Alaska and southward to Monterey Bay, California. Two specimens in the Point Barrow collections were dredged at depths of about 62 and 226 meters, 5 to 12 miles from shore.

Amphiporus groenlandicus (Oersted), 1844. This is another species that is widely distributed in Arctic seas, having been reported from both the eastern and western coasts of Greenland, from Hinlopen Strait, Barents Sea, and from the waters off King Karl Land, Jena Island, Franz Josef Land, and Spitzbergen at depths of 4 to 450 meters. The same or a closely similar species, *A. caecus* Verrill, also without ocelli, has been dredged at a depth of about 35 meters off the New England coast (Coe, 1943). *A. groenlandicus* was found in the Point Barrow area at depths of 40 to 247 meters and up to 12 miles from shore.

Amphiporus imparispinosus Griffin, 1898. This has been reported previously from the Bering Sea and it is abundant in many localities in the intertidal zone and below, along the coast of Alaska and southward to Ensenada, Mexico. The typical form, which has three pouches of accessory stylets is often associated with the variety *similis*, which has only two. The species was found in the Point Barrow area at depths of 37 to 104 meters and up to 7 miles from shore.

Amphiporus lactifloreus (Johnston) 1828. With the exception of *Amphiporus angulatus*, this species appears to be the most abundant nemertean in the Point Barrow area. The species was found at 13 stations, where the depths varied from 12 to 226 meters and at distances up to 12 miles from shore. It is widely distributed along the shores of the Arctic and North Atlantic oceans, extending southward to the Mediterranean Sea and on the American coast as far as Cape Cod. Except in the far north it occurs in the intertidal zone and in some areas to depths of 200 meters.

Amphiporus macracanthus Coe, 1905. This species is known only from the Arctic coast of Alaska, where it was collected as early as 1882 near Cape Smyth and at a later date at Wainwright Inlet (Coe, 1905). In the Point Barrow area it was found at depths of 38 to 53 meters and up to 4 miles from shore.

Amphiporus pacificus Coe, 1905. Previously dredged at depths of 70 to 180 meters in the Bering Sea and off the coasts of Washington and California. Collected in the Point Barrow area at depths of 9 to 226 meters and up to 12 miles from shore.

Tetrastemma aberrans Coe, 1901. Several specimens were dredged at depths of less than 40 meters. Previously known only from the coast of Alaska.

Tetrastemma bicolor Coe, 1901. Previously known only from Kodiak Island, Alaska. One individual was dredged at a depth of 50 meters about 3 miles from Point Barrow.

Tetrastemma candidum (Müller), 1774. Circumpolar; Greenland; Norway to Madeira; South Africa; Labrador to southern New England and southward to northern Florida; northern coast of the Gulf of Mexico; Alaska to California and northern Mexico. In the Point Barrow area the species was found at depths of 34 to 145 meters and up to 16 miles from shore.

Tetrastemma coronatum (Quatrefages), 1846. The collection from the Point Barrow area was accompanied by a colored photograph of an individual of this species that had been dredged at a depth of 50 meters, about 3 miles from shore. Common on European coasts and the Mediterranean. Reported also in Japan (Yamaoka, 1940).

All the specimens in this collection are in the U. S. National Museum.

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THE GROWTH AND VIABILITY OF SIXTY-THREE SPECIES OF MARINE BACTERIA AS INFLUENCED BY HYDROSTATIC PRESSURE[1]

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ABSTRACT

The hydrostatic pressure of sea water, which increases approximately 0.1 atmosphere per meter of depth, was found to affect the viability, reproduction, and morphology of 63 stock cultures of marine bacteria representing several genera. Many of the cultures were killed at 27° C by pressures ranging from 200 to 600 atm, although some few reproduced at 600 atm. Initial inoculum concentrations of the various bacteria appeared to influence their ability to reproduce or to tolerate high pressures. Pressures exceeding 400 atm inhibited the fission of certain bacteria without stopping their growth, thereby resulting in bizarre cells, some of which formed long filaments.

INTRODUCTION

The precursory observations of Certes (1884), Regnard (1891), ZoBell and Johnson (1949), and ZoBell and Oppenheimer (1950) indicate that hydrostatic pressures of the order of 200 to 600 atm have a pronounced effect on the vertical distribution and activities of bacteria in the sea. The significance of these observations is suggested by the fact that pressures exceeding 200 atm prevail in more than 90% of the area of the oceans. Approximately half of the oceans of the world are deeper than 4,000 m, at which depth the hydrostatic pressure is about 400 atm.

From the illustrative data in Table I it will be observed that the pressure of sea water increases with depth by approximately 0.1 atm/m, the pressure-depth gradient being influenced somewhat by latitude, temperature, and salinity. One atmosphere is equivalent to 14.696 lb/in^2, 760 mm Hg, 1.0332 kg/cm^2, or to 1.0133 bars.

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TABLE I. Selected Pressure-depth Gradients in Atmospheres Per Meter in the Sea for Different Depths, Salinities, Temperatures, and Latitudes (Adapted From Data Given By Bjerknes and Sandström, 1910)

Dynamic depth (m)	*Salinity* °/₀₀	*Temperature* °*C*	*Latitude 30°* *atm/m*	*Latitude 60°* *atm/m*
0	32	0	0.099,414	0.099,403
0	32	20	0.098,831	0.099,092
0	35	0	0.099,375	0.099,638
0	35	20	0.099,052	0.099,314
5,000	35	0	0.101,757	0.102,026
5,000	35	5	0.101,660	0.101,929
10,000	35	0	0.103,952	0.104,225

had been found was 5,800 m, but during the last year the Galathea Deep Sea Expedition extended the lower limits of the biosphere to 10,460 m. In several samples of sediments collected from depths exceeding 10,000 m in the Philippine Trench, ZoBell (1952) demonstrated the presence of bacteria that were physiologically active at pressures of the order of 1,000 atm. In fact, the well being of many bacteria collected from abyssal oceanic depths appears to depend upon high pressure. The purpose of this paper is to record the effect of pressure upon the activities of 63 different species of marine bacteria, all of which were taken from depths of less than 6,000 m.

EXPERIMENTAL METHODS

The bacteria were subjected to pressures up to 600 atm by means of apparatus described by ZoBell and Oppenheimer (1950). Essentially the apparatus consisted of thick-walled steel cylinders which have an inside diameter of 1 ⅜ inches and which are long enough (11 inches) to accommodate two dozen small culture tubes. The latter were fitted with no. 000 neoprene stoppers which functioned as pistons to subject the aqueous contents of the tubes to virtually the same pressure as the hydraulic fluid filling the steel cylinder. Preliminary experiments proved that pressure up to 1,000 atm could be applied and released ten times successively by means of the connecting hydraulic pump without the contents of the closed tubes becoming contaminated.

The culture medium consisted of sea water enriched with 0.5% peptone, 0.1% yeast extract, and 0.01% ferric phosphate. Following autoclave sterilization the pH of the medium was 7.6. Sufficient volume of such sea water medium was inoculated with bacteria in their logarithmic phase of growth to fill the number of culture tubes required for any one experiment. This ensured having comparable numbers and kinds of bacteria at the beginning of each experiment. The inoculated medium was pipetted aseptically into sterile culture tubes, leaving approximately 0.5 ml of air at the top. The tubes were closed with sterile stoppers preparatory to placing them in pressure cylinders. After displacing the air from the cylinders by filling the space between the culture tubes with water, the cylinders were closed and immersed in a water bath at 27° C. Sufficient time (about 10 minutes) was allowed for the contents of the cylinders to attain this temperature. Then each cylinder in turn was connected to the hydraulic pump and the desired pressure applied. The valve was closed, the pump disconnected from the pressurized cylinders, and the latter were returned to the water bath to provide for the incubation of the bacterial cultures at 27° C.

Following four days' incubation the cylinders were reconnected to the hydraulic pump and gauge for checking the terminal pressure. After releasing the pressure, the culture tubes were removed from the cylinders for examination for evidence of growth as indicated by increased cloudiness or turbidity of the medium. Those tubes showing no evidence of bacterial growth under pressure were incubated an additional four days at room pressure in order to ascertain if the bacteria were still viable. The abundance and viability of bacteria in some tubes was estimated by standard plate count procedures. The contents of other tubes were examined by means of a phase microscope at a magnification of 970x.

RESULTS

In order to assess the effect of the abundance of bacteria in the inoculum upon the pressure tolerance of bacteria, four representative species were introduced into sea water medium to give initial populations ranging from 10 to 10^7 cells/ml. After four days' incubation at different pressures the bacterial population was determined by plate counts (Table II). When incubated at pressures of 1, 200, or 400 atm, the final bacterial population was not perceptibly affected by the initial number of cells present within the range of 10^2 to 10^6 cells/ml. Comparable results were not obtained when the initial bacterial population was less than 10^2 cells/ml. This suggests that an initial low bacterial population results in a more prolonged lag phase probably due to the presence of fewer pressure-tolerant cells in the smaller inocula. Therefore in subsequent experiments the medium was inoculated with enough cells to give initial bacterial populations of approximately 10^3 cells/ml.

As shown by the data in Table II, there was generally a decrease in

TABLE II. NUMBERS OF VIABLE CELLS PER ML OF (a) CULTURE NO. 643, (b) *Serratia marinorubra*, (c) *Sarcina pelagia*, AND (d) CULTURE NO. 38:172 AS INDICATED BY PLATE COUNTS AFTER SEA WATER BROTH CULTURES CONTAINING THE INDICATED INOCULA HAD BEEN INCUBATED AT DIFFERENT PRESSURES FOR FOUR DAYS AT 27° C

Cultural organism	*Inoculum cells/ml*	*Hydrostatic pressures in atmospheres*			
		one	*200*	*400*	*600*
(a)	3×10^0	5×10^7	1×10^7	2×10^8	0
	3×10^2	2×10^7	5×10^7	9×10^7	8×10^2
	3×10^4	1×10^7	2×10^7	4×10^7	6×10^4
	3×10^7	3×10^7	3×10^7	7×10^6	4×10^6
(b)	2×10^1	5×10^7	9×10^6	6×10^5	7×10^1
	2×10^3	6×10^7	3×10^7	5×10^6	8×10^4
	2×10^5	9×10^7	5×10^7	7×10^6	8×10^4
	2×10^7	5×10^7	3×10^7	7×10^7	7×10^6
(c)	2×10^{-1}	1×10^7	3×10^3	1×10^5	0
	2×10^1	3×10^7	7×10^7	4×10^7	1×10^3
	2×10^3	1×10^8	5×10^7	3×10^7	3×10^4
	2×10^5	3×10^7	4×10^7	4×10^7	7×10^6
(d)	6×10^0	4×10^7	4×10^7	6×10^3	2×10^1
	6×10^2	9×10^7	4×10^7	5×10^5	2×10^2
	6×10^4	5×10^7	4×10^7	7×10^7	2×10^3
	6×10^6	1×10^8	5×10^7	5×10^7	6×10^6

the bacterial population of medium incubated at 600 atm. Employing turbidity as a criterion of growth or reproduction, it was found that only seven out of a total of 63 species tested reproduced at 600 atm. The pressure tolerance of the 63 species, representing 10 different genera, recorded in Table III, is summarized as follows:

Number of bacterial cultures which:	*Hydrostatic pressure at 27° C*			
	1 atm	*200 atm*	*400 atm*	*600 atm*
Reproduced	63	48	35	7
Showed no change	0	10	17	33
Were killed	0	5	11	23

In interpreting these results, it should be noted that the organisms had been maintained in the laboratory for several years since their isolation from the sea. Whether their pressure tolerance changed during this period is problematical, although significantly those tolerating the highest pressures in general are species commonly found at greater depths in the sea. Most of the organisms, described by ZoBell and Upham (1944), were originally isolated from shallow water

TABLE III. Multiplication of Marine Bacteria as Indicated by Relative Turbidity in Sea Water Broth After Eight Days' Incubation at Different Hydrostatic Pressures at 27° C

	Hydrostatic pressures in atmospheres			
*Name or number of culture**	*one*	*200*	*400*	*600*
Achromobacter stenohalis	++++	–	–	K
Achromobacter aquamarinus	++++	++++	+++	–
Achromobacter stationis	++++	++++	++++	–
Achromobacter thalassius	++++	K	K	K
Actinomyces halotrichis	++	–	–	–
Actinomyces marinolimosus	++++	++++	–	–
Bacillus imomarinus	++++	–	–	–
Bacillus cirroflagellosus	++++	++	–	–
Bacillus epiphytus	+++	++	++	K
Bacillus submarinus	++++	+++	+++	–
Bacillus thalassokoites	++++	+++	+	–
Bacillus filicolonicus	++++	–	K	K
Bacillus abysseus	++++	++++	+++	–
Bacillus borborokoites	++++	++++	++++	+++
Flavobacterium marinotypicum	++++	++++	++++	–
Flavobacterium marinovirosum	++++	++++	++	–
Flavobacterium neptunium	++	+	–	–
Flavobacterium okeanokoites	++++	++++	+	–
Micrococcus aquivivus	++++	++++	++++	++++
Micrococcus sedimenteus	++++	++++	++++	K
Micrococcus maripuniceus	++++	++++	–	–
Micrococcus infimus	+++	++++	–	–
Micrococcus sedentarius	++++	++++	++++	–
Micrococcus euryhalis	++++	K	K	K
Pseudomonas enalia	++++	+++	–	K
Pseudomonas neritica	++++	++++	+++	K
Pseudomonas azotogena	++++	K	K	K
Pseudomonas vadosa	++++	++++	++++	–
Pseudomonas oceanica	++++	+++	++++	–
Pseudomonas felthami	++++	++++	++	–
Pseudomonas aestumarina	++++	–	K	K
Pseudomonas membranula	+	–	K	K
Pseudomonas stereotropis	++++	+++	+	K
Pseudomonas coenobios	++++	++++	++++	–
Pseudomonas obscura	++++	++++	++	–
Pseudomonas pleomorpha	++++	++++	++	–
Pseudomonas marinopersica	++	K	K	K
Pseudomonas periphyta	++	–	K	K
Pseudomonas hypothermis	++++	K	K	K
Pseudomonas perfectomarinus	++++	++++	+++	+++
Pseudomonas xanthochrus	++++	–	–	–

TABLE III. (*Continued*)

*Name or number of culture**	*Hydrostatic pressures in atmospheres*			
	one	*200*	*400*	*600*
Sarcina pelagia	++++	+++	+++	–
Serratia marinorubra	++++	++++	+++	–
Vibrio marinopraesens	++++	++++	+++	–
Vibrio algosus	++++	++++	++	+
Vibrio adaptatus	++++	+++	+++	K
Vibrio marinoflavus	+++	+++	+	K
Vibrio ponticus	++++	+++	++	K
Vibrio phytoplanktis	++++	++++	++++	+++
Vibrio haloplanktis	++++	++++	++++	+
Vibrio marinovulgaris	++++	+++	–	–
Vibrio marinofulvus	++++	++++	++	–
Vibrio marinagilis	++++	+	–	–
Vibrio hyphalus	++++	++++	K	K
Number 516	++++	++++	++	K
Number 549	++++	++++	+++	K
Number 595	++	–	–	–
Number 623	++	++	–	–
Number 632	++++	–	–	–
Number 633	++++	++++	–	–
Number 639	++++	++	K	K
Number 643	++++	++++	++++	++++
Number 689	++++	+++	–	K

* All except the numbered cultures have been described by ZoBell and Upham (1944).

++++ = good multiplication
+++ = fair multiplication
++ = less multiplication
+ = poor multiplication
– = no multiplication, but organisms not killed
K = all bacteria in culture killed

TABLE IV. MORPHOLOGICAL VARIATIONS OF MARINE BACTERIA INDUCED BY HYDROSTATIC PRESSURES RANGING FROM 200 TO 600 ATM AFTER FOUR DAYS' INCUBATION AT 27° C

Organism	*Morphological variations*
Bacillus abysseus	Increase in cell size and spore formation
Bacillus borborokoites	General increase in cell size
Micrococcus aquivivus	General increase in cell size
Sarcina pelagia	Increase in size and marked pleomorphism
Serratia marinorubra	Formation of long filaments and loss of motility
Vibrio phytoplanktis	Longer pleomorphic rods, granular, loss of motility
Culture no. 643	Long filament formation

environments and none of them came from depths exceeding 6,000 m where pressures are greater than 600 atm.

Examination of the bacteria with a phase microscope shortly after the cultures were removed from the pressure cylinders showed that many had undergone morphological alterations (Table IV). The commonest change in organisms that failed to reproduce at elevated pressures was an increase in cell size, especially in length. Pressure to the limit of tolerance nearly always induced marked pleomorphism and rendered the cells nonmotile. Several seemed to grow in size or length without any evidence of cell fission or reproduction.

DISCUSSION

Although our knowledge of the effects of pressure on organisms is still woefully scant, data summarized by Cattell (1936) show that pressures such as those that occur in the sea may have multiple physiological effects. Slightly increased pressures may be stimulatory, whereas higher pressures cause the attenuation or death of organisms. According to literature reviewed by Bridgman (1946), pressure affects the rate and direction of many chemical reactions. By virtue of its effect on solubilities and dissociation constants, the pH and Eh values of complex solutions may be affected by pressure. These and other properties of solutions affected by pressure may combine to influence the physiology and ecology of marine organisms in many ways.

Very little is known about the ability of organisms to adjust themselves to higher pressures. In the marine environment, where pressures range from one to somewhat more than 1,000 atm, organisms may become acclimatized to the pressures of their habitat range. The results presented in this paper substantiate the observations of ZoBell and Johnson (1949) that the pressure tolerance of marine bacteria is related to their depth habitat. The intolerance of certain bacteria for pressures exceeding 200 atm, for example, suggests that such organisms are not active in the sea at depths exceeding 2,000 m. On the other hand, finding bacteria at depths of several thousand meters that grow at atmospheric pressure but not at pressures isobaric with the environment where they are found raises the question whether such bacteria were active in situ or were in a state of dormancy.

Such questions must be answered before the marine microbiologist can hope to appraise the importance of bacteria as biochemical or geochemical agents in the deep sea. The effect of temperature must be taken into account in seeking the answers to such questions, because there is evidence that the pressure tolerance of organisms is partly a function of the temperature. Although data to be detailed elsewhere show that the pressure tolerance of some bacteria is increased at elevated temperature, others seem to exhibit maximum pressure tolerance at the lowest temperature at which they are physiologically active.

While submarine pressures undoubtedly affect the distribution and physiological activities of bacteria, at no place in the sea will pressures prohibit the presence of bacteria, because mixed cultures have been shown to be alive and active at presssures higher than those characteristic of the most abyssal deeps.

SUMMARY

The optimal initial bacterial population in nutrient medium to give comparable results in pressure tolerance tests proved to be approximately 10^3 viable cells per ml.

Pressures ranging from 200 to 600 atm inhibited the normal growth of nearly all of the 63 different species of marine bacteria tested, although a few cultures of mixed microflora from deep sea sediments reproduced at pressures exceeding 1,000 atm. Out of 63 pure cultures tested, 15 failed to reproduce when subjected to a pressure of 200 atm at 27° C and 5 were killed in four days. Of the 28 that failed to reproduce at 400 atm 11 were killed, and of 56 that failed to reproduce at 600 atm 23 were killed by pressure.

The morphology of bacteria was affected by pressures ranging from 400 to 600 atm.

The distribution and physiological activities of bacteria in the sea are probably influenced by the hydrostatic pressures which increase per meter of depth by approximately 0.1 atm.

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THE GROWTH AND VIABILITY OF SIXTY-THREE SPECIES OF MARINE BACTERIA AS INFLUENCED BY HYDROSTATIC PRESSURE[1]

By

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ABSTRACT

The hydrostatic pressure of sea water, which increases approximately 0.1 atmosphere per meter of depth, was found to affect the viability, reproduction, and morphology of 63 stock cultures of marine bacteria representing several genera. Many of the cultures were killed at 27° C by pressures ranging from 200 to 600 atm, although some few reproduced at 600 atm. Initial inoculum concentrations of the various bacteria appeared to influence their ability to reproduce or to tolerate high pressures. Pressures exceeding 400 atm inhibited the fission of certain bacteria without stopping their growth, thereby resulting in bizarre cells, some of which formed long filaments.

INTRODUCTION

The precursory observations of Certes (1884), Regnard (1891), ZoBell and Johnson (1949), and ZoBell and Oppenheimer (1950) indicate that hydrostatic pressures of the order of 200 to 600 atm have a pronounced effect on the vertical distribution and activities of bacteria in the sea. The significance of these observations is suggested by the fact that pressures exceeding 200 atm prevail in more than 90% of the area of the oceans. Approximately half of the oceans of the world are deeper than 4,000 m, at which depth the hydrostatic pressure is about 400 atm.

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Cultural organism	*Inoculum cells/ml*	*Hydrostatic pressures in atmospheres*			
		one	*200*	*400*	*600*
(a)	3×10^{0}	5×10^{7}	1×10^{7}	2×10^{8}	0
	3×10^{2}	2×10^{7}	5×10^{7}	9×10^{7}	8×10^{2}
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(c)	2×10^{-1}	1×10^{7}	3×10^{3}	1×10^{5}	0
	2×10^{1}	3×10^{7}	7×10^{7}	4×10^{7}	1×10^{3}
	2×10^{3}	1×10^{8}	5×10^{7}	3×10^{7}	3×10^{4}
	2×10^{5}	3×10^{7}	4×10^{7}	4×10^{7}	7×10^{6}
(d)	6×10^{0}	4×10^{7}	4×10^{7}	6×10^{3}	2×10^{1}
	6×10^{2}	9×10^{7}	4×10^{7}	5×10^{5}	2×10^{2}
	6×10^{4}	5×10^{7}	4×10^{7}	7×10^{7}	2×10^{3}
	6×10^{6}	1×10^{8}	5×10^{7}	5×10^{7}	6×10^{6}

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Bacillus thalassokoites	++++	+++	+	–
Bacillus filicolonicus	++++	–	K	K
Bacillus abysseus	++++	++++	+++	–
Bacillus borborokoites	++++	++++	++++	+++
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Flavobacterium okeanokoites	++++	++++	+	–
Micrococcus aquivivus	++++	++++	++++	++++
Micrococcus sedimenteus	++++	++++	++++	K
Micrococcus maripuniceus	++++	++++	–	–
Micrococcus infimus	+++	++++	–	–
Micrococcus sedentarius	++++	++++	++++	–
Micrococcus euryhalis	++++	K	K	K
Pseudomonas enalia	++++	+++	–	K
Pseudomonas neritica	++++	++++	+++	K
Pseudomonas azotogena	++++	K	K	K
Pseudomonas vadosa	++++	++++	++++	–
Pseudomonas oceanica	++++	+++	++++	–
Pseudomonas felthami	++++	++++	++	–
Pseudomonas aestumarina	++++	–	K	K
Pseudomonas membranula	+	–	K	K
Pseudomonas stereotropis	++++	+++	+	K
Pseudomonas coenobios	++++	++++	++++	–
Pseudomonas obscura	++++	++++	++	–
Pseudomonas pleomorpha	++++	++++	++	–
Pseudomonas marinopersica	++	K	K	K
Pseudomonas periphyta	++	–	K	K
Pseudomonas hypothermis	++++	K	K	K
Pseudomonas perfectomarinus	++++	++++	+++	+++
Pseudomonas xanthochrus	++++	–	–	–

TABLE III. (*Continued*)

*Name or number of culture**	*Hydrostatic pressures in atmospheres*			
	one	*200*	*400*	*600*
Sarcina pelagia	++++	+++	+++	–
Serratia marinorubra	++++	++++	+++	–
Vibrio marinopraesens	++++	++++	+++	–
Vibrio algosus	++++	++++	++	+
Vibrio adaptatus	++++	+++	+++	K
Vibrio marinoflavus	+++	+++	+	K
Vibrio ponticus	++++	+++	++	K
Vibrio phytoplanktis	++++	++++	++++	+++
Vibrio haloplanktis	++++	++++	++++	+
Vibrio marinovulgaris	++++	+++	–	–
Vibrio marinofulvus	++++	++++	++	–
Vibrio marinagilis	++++	+	–	–
Vibrio hyphalus	++++	++++	K	K
Number 516	++++	++++	++	K
Number 549	++++	++++	+++	K
Number 595	++	–	–	–
Number 623	++	++	–	–
Number 632	++++	–	–	–
Number 633	++++	++++	–	–
Number 639	++++	++	K	K
Number 643	++++	++++	++++	++++
Number 689	++++	+++	–	K

* All except the numbered cultures have been described by ZoBell and Upham (1944).

++++ = good multiplication
+++ = fair multiplication
++ = less multiplication
+ = poor multiplication
– = no multiplication, but organisms not killed
K = all bacteria in culture killed

TABLE IV. Morphological Variations of Marine Bacteria Induced by Hydrostatic Pressures Ranging from 200 to 600 atm After Four Days' Incubation at 27° C

Organism	*Morphological variations*
Bacillus abysseus	Increase in cell size and spore formation
Bacillus borborokoites	General increase in cell size
Micrococcus aquivivus	General increase in cell size
Sarcina pelagia	Increase in size and marked pleomorphism
Serratia marinorubra	Formation of long filaments and loss of motility
Vibrio phytoplanktis	Longer pleomorphic rods, granular, loss of motility
Culture no. 643	Long filament formation

environments and none of them came from depths exceeding 6,000 m where pressures are greater than 600 atm.

Examination of the bacteria with a phase microscope shortly after the cultures were removed from the pressure cylinders showed that many had undergone morphological alterations (Table IV). The commonest change in organisms that failed to reproduce at elevated pressures was an increase in cell size, especially in length. Pressure to the limit of tolerance nearly always induced marked pleomorphism and rendered the cells nonmotile. Several seemed to grow in size or length without any evidence of cell fission or reproduction.

DISCUSSION

Although our knowledge of the effects of pressure on organisms is still woefully scant, data summarized by Cattell (1936) show that pressures such as those that occur in the sea may have multiple physiological effects. Slightly increased pressures may be stimulatory, whereas higher pressures cause the attenuation or death of organisms. According to literature reviewed by Bridgman (1946), pressure affects the rate and direction of many chemical reactions. By virtue of its effect on solubilities and dissociation constants, the pH and Eh values of complex solutions may be affected by pressure. These and other properties of solutions affected by pressure may combine to influence the physiology and ecology of marine organisms in many ways.

Very little is known about the ability of organisms to adjust themselves to higher pressures. In the marine environment, where pressures range from one to somewhat more than 1,000 atm, organisms may become acclimatized to the pressures of their habitat range. The results presented in this paper substantiate the observations of ZoBell and Johnson (1949) that the pressure tolerance of marine bacteria is related to their depth habitat. The intolerance of certain bacteria for pressures exceeding 200 atm, for example, suggests that such organisms are not active in the sea at depths exceeding 2,000 m. On the other hand, finding bacteria at depths of several thousand meters that grow at atmospheric pressure but not at pressures isobaric with the environment where they are found raises the question whether such bacteria were active in situ or were in a state of dormancy.

Such questions must be answered before the marine microbiologist can hope to appraise the importance of bacteria as biochemical or geochemical agents in the deep sea. The effect of temperature must be taken into account in seeking the answers to such questions, because there is evidence that the pressure tolerance of organisms is partly a function of the temperature. Although data to be detailed elsewhere show that the pressure tolerance of some bacteria is increased at elevated temperature, others seem to exhibit maximum pressure tolerance at the lowest temperature at which they are physiologically active.

While submarine pressures undoubtedly affect the distribution and physiological activities of bacteria, at no place in the sea will pressures prohibit the presence of bacteria, because mixed cultures have been shown to be alive and active at presssures higher than those characteristic of the most abyssal deeps.

SUMMARY

The optimal initial bacterial population in nutrient medium to give comparable results in pressure tolerance tests proved to be approximately 10^3 viable cells per ml.

Pressures ranging from 200 to 600 atm inhibited the normal growth of nearly all of the 63 different species of marine bacteria tested, although a few cultures of mixed microflora from deep sea sediments reproduced at pressures exceeding 1,000 atm. Out of 63 pure cultures tested, 15 failed to reproduce when subjected to a pressure of 200 atm at 27° C and 5 were killed in four days. Of the 28 that failed to reproduce at 400 atm 11 were killed, and of 56 that failed to reproduce at 600 atm 23 were killed by pressure.

The morphology of bacteria was affected by pressures ranging from 400 to 600 atm.

The distribution and physiological activities of bacteria in the sea are probably influenced by the hydrostatic pressures which increase per meter of depth by approximately 0.1 atm.

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erichia coli in the Intestine of a
l Sea Lion[1]

TLE literature is available concerning the pres-
of *Escherichia coli* in the intestinal tract of
e mammals. Coliforms have been found in polar
(*1*) but were not confirmed to be *E. coli*. ZoBell
ates that *E. coli* does not appear to be a normal
itant of the intestines of seals in captivity. Re-
vork by the authors, however, suggests that *E.*
s commonly found in the intestines of captive
maintained in either fresh or sea water. This
ism is a very common contaminant of stored
e fish (*2*) and may be introduced into the seal's
tary system by the feeding of such material.
fore, when a wild sea lion (*Zalophus cali-*
nus) was captured near the Scripps Institution
eanography, an attempt was made to determine
er *E. coli* might be present under natural con-
s.

specimen, an adult female, was sacrificed, and
es were removed aseptically from the stomach
rom the initial, central, and terminal sections of
testines. Difco Levine EMB agar, prepared
vith fresh and with sea water, was used as the
ng medium. The medium was poured into plates and streaked with the samples from the sea lion.

After 24 hr incubation, at both 27° and 37° C, the EMB plates were examined, and the presence of coliform organisms was established in both the lower end of the small intestine and in the entire large intestine. The stomach appeared to be sterile. Typical coliform organisms appeared on the sea-water medium, but the colonies on fresh-water medium lacked their differentiating metallic sheen. All other features, including routine differential media, indicated that the organisms were *E. coli*. The isolated *E. coli* cultures grew as well, at either 27° or 37° C, on sea-water as they did on fresh-water medium; hence these organisms may have been indigenous to the sea or were more resistant forms from terrestrial contamination. *E. coli* will normally tolerate limited exposure to sea water, but the conventionally known strains are reportedly either killed quantitatively or diluted to virtual extinction by sea water in full strength (*2*).

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Chapter 3

CURRENTS IN THE SURF ZONE*

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ABSTRACT

Surface and bottom currents in the surf zone were measured at 15 equally spaced points along two straight beaches with approximately parallel bottom contours. The measurements showed that offshore currents predominate over onshore currents at the bottom, while at the surface there is a slight predominance in the onshore direction. With regard to the longshore component, it was found that surface and bottom currents have a similar velocity distribution. The variability of the longshore component as measured by its standard deviation is equal to or larger than the mean longshore velocity. This wide variation in longshore currents indicates the impracticability of estimating the mean velocity from a single observation of longshore current.

It was found that the momentum approach to the prediction of longshore currents by Putnam, Munk and Traylor (1949) leads to useful forecasts provided the beach friction coefficient k is permitted to vary with the longshore velocity, V. The indicated relation is $k \sim V^{-3/2}$.

INTRODUCTION

A series of longshore current measurements was made in 1949 and 1950 along two straight beaches in the San Diego area. The purpose of the investigation was to study quantitatively the variability of current velocities in the surf zone, and to test the method of prediction of longshore currents from the characteristics of the waves producing them.

The terminology and general principles of the circulation resulting from wave action in and near the surf zone was discussed in a previous paper (Shepard and Inman, 1951). The scope of the present paper is limited to a discussion of currents inside of the breaker zone.

Two straight beaches with relatively parallel bottom contours were selected for study, Torrey Pines beach north of La Jolla and Pacific Beach to the south of La Jolla (Fig. 1). Fifteen stations

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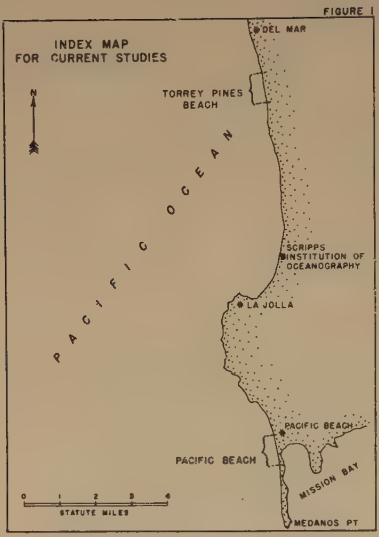
FIGURE 1
INDEX MAP
FOR CURRENT STUDIES
N
DEL MAR
TORREY PINES BEACH
PACIFIC OCEAN
SCRIPPS INSTITUTION OF OCEANOGRAPHY
LA JOLLA
PACIFIC BEACH
PACIFIC BEACH
MISSION BAY
MEDANOS PT
0 1 2 3 4
STATUTE MILES

Fig. 1

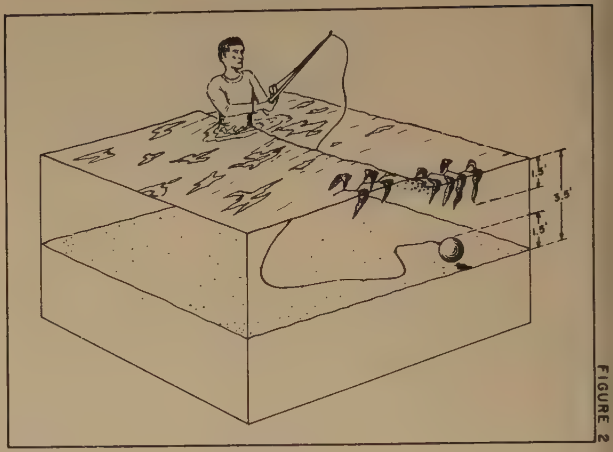
1.5'
3.5'
1.5'
FIGURE 2

Fig. 2

Fig. 1. Index map for current studies.

Fig. 2. Devices used in current investigations were of the free drifting type. Kelp was used for surface currents, and a volley ball filled with water and weighted with sufficient mercury to give it a slight negative buoyancy was used for bottom currents.

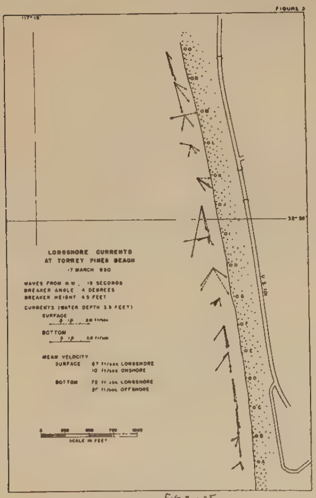
FIGURE 3
LONGSHORE CURRENTS
AT TORREY PINES BEACH
17 MARCH 1950
WAVES FROM N.W., 15 SECONDS
BREAKER ANGLE 4 DEGREES
BREAKER HEIGHT 4.5 FEET
CURRENTS (WATER DEPTH 3.5 FEET)
SURFACE
0 1.0 2.0 ft/sec
BOTTOM
0 1.0 2.0 ft/sec
MEAN VELOCITY
SURFACE .67 ft/sec LONGSHORE
.10 ft/sec ONSHORE
BOTTOM .72 ft/sec LONGSHORE
.20 ft/sec OFFSHORE
0 250 500 750 1000
SCALE IN FEET

Fig. 3

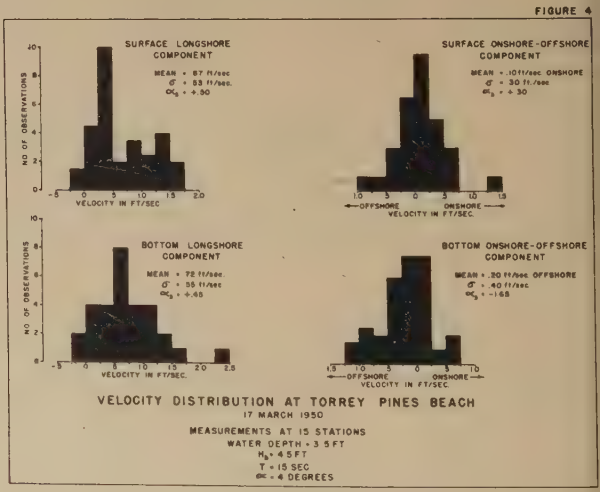

Fig. 4

Fig. 3. A typical series of current observations showing the variation of currents along Torrey Pines Beach. Each measurement is shown by a vector opposite the appropriate station.

Fig. 4. Histograms showing the distribution of current velocities for the series of observations shown in Fig. 3.

were selected at equal intervals along an 0.8 mile stretch on each beach. The stations were numbered "A" through "O" and were approximately 300 feet apart. Each series of observations consisted of 2 surface and 2 bottom current measurements at each station giving a total of 30 surface and 30 bottom current measurements along the beach. A complete series of 60 measurements required about 2 hours and were made inside the breaker zone in water approximately $3\frac{1}{2}$ feet deep.

The devices used in the investigations were of a free drifting type, the velocity being determined by the distance of travel in a given period of time. Bottom current magnitude and directions were obtained by means of a volley ball filled with water and weighted with sufficient mercury to give it a slight negative buoyancy. The ball was attached to a light fishing line which was calibrated, and contained on a reel fixed to a short pole (Fig. 2). An observer, standing about waist deep at a chosen station in the surf zone, released the ball at a given signal and played out free line as the ball was carried by the current. When an observer on shore indicated that a period of 30 seconds had elapsed, the line was jerked taut and the direction to the ball noted. The number of feet travelled during the 30 second interval was observed as the line was reeled in. Direction of the current was estimated to the nearest $22\frac{1}{2}°$ by noting the angle that the line made with the shore line. Surface currents were measured during the same interval by releasing a piece of kelp at the spot where the bottom current ball was dropped. A second observer determined the distance and direction of travel of the kelp during the same time interval. The interval of 30 seconds was chosen as being long enough to give a representative current and short enough to indicate major current fluctuation and tendencies in the surf zone.

During current observations, significant breaker heights* were obtained by an observer standing at mean water level and lining up the top of the breaker crest with the horizon. The height of the observer's eye above water level was read from a graduated pole. This height was multiplied by 4/3 to give the height of the breaking wave.

The average significant breaker height, H, for the series of current measurements was obtained by averaging the significant waves at each station. The significant wave period T, was obtained by timing the passage of the significant wave crests past a fixed point with a stop watch. The angle of approach α , between the crest of the breaking wave and the straight beach was measured during the 1950 observations by the transit sighting bar method devised by Forrest (1950). The breaker height H, period T, and the angle of approach for each series of observations are listed in Table 1.

The significant wave height is the average of the highest one-third of the waves.

TABLE I
Tabulation of Field Data

Date	H ft.	T sec.	α 1/ deg.	i	Longshore Component						Onshore-Offshore Component 2/					
					Surface			Bottom			Surface			Bottom		
					V_m	σ	α_3	V_m	σ	α_3	V_m	σ	α_3	V_m	σ	α_3
A. Torrey Pines Beach 1949																
1949								ft/sec	ft/sec					ft/sec	ft/sec	
27 Jun.	2.8	15	6½°N	.027				.38	.38	-.75				-.16	.25	+1.36
29 Jun.	3.1	8½	1½°S	.027				.04	.38	-.15				-.06	.28	- .82
30 Jun.	3.7	8	4°S	.027				.22	.43	+.40				-.25	.35	-1.33
1 Jul.	3.6	14	N	.027				.04	.49	+2.50				-.28	.34	+1.50
		9	0°													
5 Jul.	4.9	8	5°S	.027				.84	.51	+1.35				-.05	.51	- .44
6 Jul.	3.8	7	5°S	.027				.21	.45	+ .51				-.33	.36	- .61
7 Jul.	3.4	12½	N	.027				.55	.36	+ .16				-.03	.62	+1.00
		7½	0°													
11 Jul.	2.6	8	N	.035				.04	.40	0				-.38	.21	+1.33
12 Jul.	3.0	9½	1°N	.035				.01	.40	0				-.25	.24	+ .23
13 Jul.	2.7	10	N	.035				.15	.40	0				-.31	.23	- .72
14 Jul.	3.5	13½	N	.035				.09	.45	-1.30				-.32	.48	- .12
		7½	S													
15 Jul.	4.9	13	N	.035				.21	.36	-1.30				-.16	.20	+ .83
19 Jul.	2.9	10	N	.035				.50	.34	0				-.26	.29	+1.78
21 Jul.	4.6	12	N	.035				.80	.66	+ .98				-.16	.39	- .87
26 Jul.	3.7	8	S	.028				.20	.59	0				-.36	-.92	- .21
		15	N													
B. Torrey Pines Beach 1950.																
1950 14 Feb.	5.1	12	6°S	.027	.37	.84	+ .09	.20	.63	+1.15	-.12	.69	-2.62	-.22	.41	-1.50
		16	5°N													
7 Mar.	4.7	14	7°S	.027	.60	.55	+ .12	.45	.60	+1.38	+.32	.78	+ .07	-.21	.39	- .66
17 Mar.	4.5	15	4°S	.027	.67	.53	+ .50	.72	.55	+ .45	+.10	.30	+ .30	-.20	.40	-1.65
29 Mar.	4.8	12	4°S	.027	1.22	1.18	+ .97	1.16	1.05	+ .68	-.11	.16	-2.44	-.28	.45	-1.18
30 Mar.	4.2	12	4½°S	.027	.38	.77	+1.56	.41	.76	- .13	+.01	.41	0	-.27	.68	- .30
		17	3°N													
21 Apr.	2.0	12	4°N	.027	.46	.57	- .49	.26	.46	0	+.07	.47	+3.28	-.09	.23	- .12
11 May	1.7	8	7°N	.027	.10	.50	- .13	.35	.52	- .15	-.01	.35	- .48	-.26	.37	0
		18	3°N													
16 May	2.9	15	5°N	.027	.60	.51	+ .13	.52	.40	- .75	+.08	.25	- .97	-.35	.40	+ .84
25 May	1.6	6	5°S	.027	.11	.33	+1.00	.10	.37	+ .82	-.08	.18	+1.62	-.38	.23	- .07
		14	2½°N													
C. Pacific Beach 1950																
1950 24 Feb.	6.2	14	5°S	.014				.54	.48	0				-.35	.53	- .85
2 Mar.	3.1	16	7°N	.014	.82	.47	- .10	.41	.28	+ .49	.03	.66	- .21	-.17	.24	-1.33
14 Mar.	4.5	12	3°S	.014	.46	.94	- .10	.51	.80	- .30	.27	.84	- .20	+.17	.71	+ .63
22 Mar.	3.5	14	4°S	.014	.20	.61	- .92	.13	.54	0	.07	.45	+1.78	-.32	.60	+1.22
18 Apr.	2.7	16	3½°N	.014	.01	1.20	- .07	.25	.70	+ .35	.26	1.14	-1.63	-.21	.68	- .33
9 May	4.7	13	7°S	.014	1.54	1.40	- .48	1.20	1.15	+ .07	.22	.82	+ .34	-.57	1.07	+2.91
18 May	2.6	11½	2°S	.014	.06	.82	+1.72	.01	.64	+1.00	.01	.57	+1.06	-.71	.41	-1.39
		8	N													
26 May	2.0	14½	4°N	.014	.03	.54	-1.78	.19	.42	+ .10	-.17	.32	-1.17	-.54	.37	+1.83
27 July	1.8	12	2½°N	.014	.09	.72	- .31	.03	.49	+ .38	.16	.50	- .43	-.40	.39	+ .43

1/The letters N (north) and S (south) indicate the direction of opening of the angle between the breaking wave and the beach. The period and breaker angle of minor wave trains, when present, are listed below the major train.

2/Positive values of V_m indicate onshore directions and negative values offshore directions.

STATISTICAL ANALYSIS OF OBSERVATIONS

A typical series of measurements is shown graphically in Fig. 3, in which the velocity and direction of each current observation is represented by a vector opposite the appropriate station. In order to treat the distribution of currents systematically, each current vector was resolved into a longshore component and an onshore-offshore component. The range of velocities in each component was divided into equal classes, and the histogram of the distribution of velocities was obtained by plotting the classes in feet per second as the abscissa and the number of observations in each class as ordinate. Histograms, showing the velocity distribution in a longshore direction and an onshore-offshore direction for both surface and bottom currents for the series of measurements shown in Fig. 3 are given in Fig. 4.

Since histograms do not give numerical descriptions of the current distribution, the data were treated statistically to obtain the arithmetic mean velocity V_m, the standard deviation σ , and the skewness α_3 of the velocity distribution.

These measures are described in statistics textbooks (for example Hoel, 1947, pp. 8-15) and defined as follows:*

$$V_m = \frac{1}{N} \sum_{i=1}^{h} V_i f_i \tag{1}$$

$$\sigma^2 = \frac{1}{N-1} \sum_{i=1}^{h} (V_i - V_m)^2 f_i \tag{2}$$

$$\alpha_3 = \frac{1}{N\sigma^3} \sum_{i=1}^{h} (V_i - V_m)^3 f_i \tag{3}$$

here N is the number of observations (N = 30 for most series), V_1 is he class mark (value of the mid-point of the class interval) of the th class, f_i is the number of observations in the class, and h is the umber of classes.

N-1 was used in the denominator of equation (2) to give an unbiased stimate of the standard deviation in accordance with small sample heory (Hoel, 1947, p. 129).

The standard deviation is a measure of the spread of the distribution, and for most symmetrical distributions approximately 68% of the observations are included between the values $V_m - \sigma$ and $V_m + \sigma$. The skewness, α_3, serves as a measure of the symmetry of the distribution. An α_3 value of 0 is indicative of a symmetrical distribution, while a positive value indicates the distribution is skewed to the right, and a negative value that it is skewed towards smaller or negative values. For purpose of comparison, the mean, standard deviation, and skewness are listed opposite each of the histograms in Fig. 4. These three statistical measures were computed for each component of velocity of each series of observations and are listed in Table I.

DISTRIBUTION OF CURRENTS

Fig. 4 illustrates some of the features that are typical of the current distribution in the surf zone. For example, the surface and bottom longshore components have similar mean velocities, but the distribution of velocities tends to be more symmetrical for the bottom component. This may be because the effect of wind is less near the bottom. The negative current values for the surface and bottom longshore components indicate that a small percentage of currents were moving in a direction opposite to that of the predominant current. The bottom onshore-offshore currents had a pronounced offshore tendency, whereas the mean velocity of the surface currents was onshore.

The nature of the distributions of the bottom longshore current component for all series of observations are summarized in Fig. 5. In this figure the minimum observed velocity, the standard deviation of the velocity distribution, the maximum velocity, and the skewness of the distributions are plotted against the mean bottom longshore velocity. This diagram does not consider such important factors as wave height, period, and angle of approach, and although the plotted points show considerable scatter, they nevertheless illustrate several important features of the bottom longshore current:

(a) In almost all cases, there were currents opposed in direction to the dominant current.

(b) The variability of the current as measured by the standard deviation averaged ½ foot per second for mean velocities below approximately ½ foot per second and was approximately equal to the mean velocity for velocities above ½ foot per second.

(c) The maximum observed velocity increased with increasing mean velocity; the maximum being approximately five times greater than the mean for mean velocities near 0.2 feet per second, and three times greater for mean velocities near 1 foot per second.

(d) There is no apparent relationship between the skewness of the velocity distribution and the mean velocity. In general the velocity distribution tends to be fairly symmetrical over the range of mean velocities investigated.

The relation of the means and of the standard deviations of the urface and bottom longshore currents are given in Fig. 6. While a inear relationship exists between these quantities, in general the ean value of the bottom longshore current appears to be more consist-nt in its agreement with the wave conditions generating the currents han the surface velocity, and the spread or variability (as measured y the standard deviation) was somewhat less for the bottom currents han for the surface currents. For these reasons the mean bottom long-hore current was used for comparing the observed with the predicted urrents in the following section.

The large variation in the observed longshore currents are caused n part by the variation in wave height with time, and by the variation f the cell-like circulation pattern of the nearshore current system ith distance along the beach. Since the mass transport of water is roportional to the square of the wave height, groups of high waves ollowed by groups of low waves result in fluctuations of current elocity with time. (Shepard & Inman, 1950, Fig. 11). Also, in many nstances, a secondary wave train was present which may have contributed o the variability.

The nearshore circulation has been shown to have a cell-like attern, consisting of relatively wide stretches along the beach where ater is transported shoreward by the waves, then along the shore in-ide of the breakers (by longshore currents) into relatively narrow ones where the water is transported seaward by rip currents (Shepard nd Inman, 1950, Figs. 2 and 3). This circulation pattern results in igher velocities up current; and lower or in some cases a reversal of ongshore current direction down current from the rip zones. This ffect is shown in Fig. 3 at stations G and L. Also, high waves approach-ng with crests parallel to the beach often result in strong longshore urrents for limited distances between rip zones, although the mean ongshore current for the entire beach may be quite low.

For the above reasons it is advisable to measure currents at as any different stations as possible, in order to obtain measurements hat are representative of the beach as a whole. The bias exhibited t the 15 stations on Torrey Pines Beach for the 1950 series of bservations is shown in Fig. 7. The plots on this figure show the egree of the divergence between the average current at each station nd the mean of all currents for the entire beach. For example, on he average, the mean bottom longshore component at Station M is 60% ess than the mean for the entire beach, while the rip tendency as easured by the bottom offshore component is 150% greater.

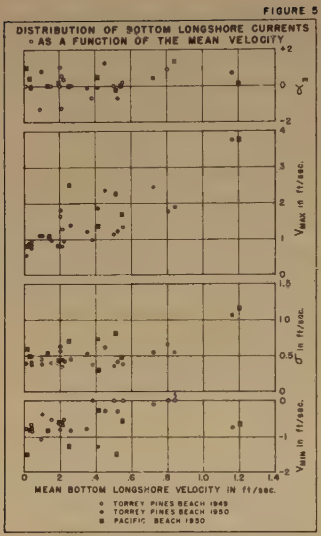

Fig. 5

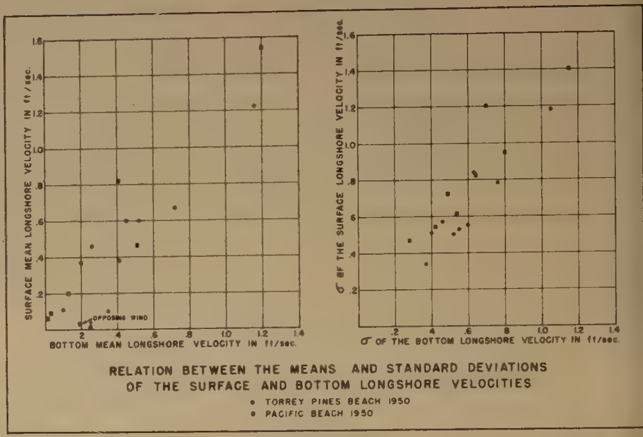

Fig. 6

Fig. 5. Summary of the distribution of bottom longshore current components as a function of the mean velocity. The negative values for the minimum observed velocity, V_{MIN}, indicate that these currents were flowing in an opposite direction to the mean current. The lower left hand diagram in Fig. 4 shows the histogram of the velocity distribution for one of the plots in this figure.

Fig. 6. Relation of the means and standard deviations of the surface and bottom longshore current components. Compare the upper and lower right-hand histograms of Fig. 5.

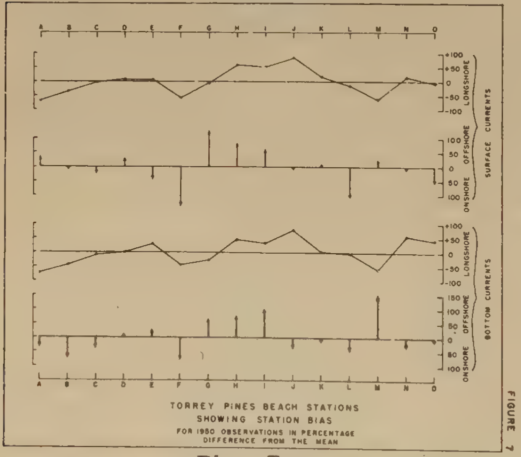

Fig. 7

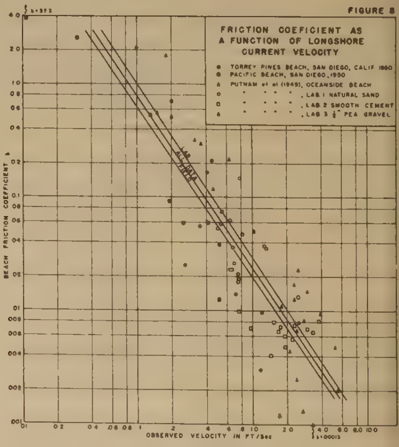

Fig. 8

Fig. 7. The bias exhibited at the 15 stations along Torrey Pines Beach. The plots show the magnitude of the deviation of the average current at each station for the mean of all currents for the entire beach during the 1950 series.

Fig. 8. Relation between the beach friction coefficient k and the observed longshore velocity. The mathematical relation is given by equations (6), (7) and (8). For the Torrey Pines and Pacific Beach observations, the mean bottom longshore component of velocity Vm, listed in Tables 1B and 1C was used.

The variation in currents as represented by the standard deviation of the distribution, σ , is a measure of the accuracy of prediction of the mean bottom longshore current from an individual measurement of current. Obviously, the greater the standard deviation or spread of velocities, the less is the probability of accurately estimating the mean from a single observation of current. For example, Fig. 5 shows that mean bottom longshore currents of $\frac{1}{2}$ foot per second are characterized by a standard deviation of approximately $\frac{1}{2}$ foot per second; this means that out of 100 estimates based on single observations of current 68 of the estimates should fall within 1 standard deviation either side of the mean, or within the velocity range of zero to 1.0 foot per second. The coefficient of variation, $C_v = 100\ \sigma / V_m$, is a useful measure in this respect, because it gives the deviation from the mean in terms of the percentage of the mean. For the example above, $C_v = 100\%$, and thus 68 of the estimates should fall within plus or minus 100% of the true mean velocity.

The coefficient of variation was computed for all bottom longshore current distributions with mean values greater than 0.1 feet per second.* The average of all of the coefficients of variation in this case was 177%. Inspection of Fig. 5 shows that for low velocities, C_v decreases with increasing mean velocity, but tends to be constant for mean velocities of $\frac{1}{2}$ foot per second and higher. The average value of C_v was 91% for mean velocities above $\frac{1}{2}$ foot per second.

It is apparent that if the estimation of the mean velocity is based on more than one observation, the accuracy of the estimation will be improved. The following relationship exists between the standard deviation of a population, σ , based on a large number of individual measurements, and the standard deviation, S, based on the means of groups of observations (Hoel, 1947, p. 65):

$$\frac{\sigma}{\sqrt{N}} = S \qquad (4)$$

where N is the number of individual measurements in each group.

If the coefficient of variation is constant over a range of mean velocities, the average coefficient of variation can be substituted for the standard deviation in equation (4). This condition is approximately fulfilled for mean velocity values exceeding $\frac{1}{2}$ foot per second.

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*The coefficient of variation loses its significance as the mean velocity, V_m, approaches zero. For this reason velocities below 0.1 foot per second were arbitrarily omitted from this computation.

Suppose we wish to estimate the number of individual observations, N, that the mean must be based on so that the coefficient of variation is 25%. Substituting 91% for σ and 25% for S in equation (4) gives a value of N equal to approximately 13 measurements.

PREDICTION OF LONGSHORE CURRENTS.

The momentum approach to the prediction of longshore currents developed by Putnam, Munk, and Traylor (1949) was selected for use in this study. It relates the mean velocity V, of the longshore currents, to the wave height H, period T, angle of approach α, and slope of the beach i, according to the relation:

$$V = \frac{a}{2}\left[\sqrt{1 - \frac{4C \sin\alpha}{a}} - 1\right] \qquad (5)$$

where

$a = (2.61\ Hi \cos\alpha)/kT$

and $C = \sqrt{2.28\ gH}$ is the wave velocity, k is the beach friction coefficient, and g is the acceleration of gravity.

The range of longshore current velocities obtained on the model and prototype beaches studied by Putnam, et al (1949), were individually limited and indicated that the beach friction coefficient "k" was relatively constant for a particular beach. However, the more recent observations in the San Diego area considered together with those of Putnam, et al (1949), indicate that "k" is a function of current velocity and cannot be considered a constant for a given beach. Using the tabulated observed values of longshore current, published in Putnam, et al (1949), the value of k was computed from equation (5) for all of their field and laboratory observations, and also for the series obtained in 1950 at the two beaches in the San Diego area by using the mean of the bottom longshore component.* The coefficient k is plotted as a function of the observed velocity in Fig. 8. Inspection of this figure strengthens the contention that the coefficient is a function of velocity; however, it should be mentioned that since k is not determined by direct measurement, it therefore not only reflects beach friction, but also any errors in measurement and any inadequacies of the theory.

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*The 1949 Torrey Pines Beach data (Table I A) was not used in this computation because of the inaccuracy in the measurement of the breaker angle. The transit-sighting bar method was not adopted for this purpose until the 1950 season.

The relation between the beach friction coefficient and the longhore current velocity was obtained separately for the field data, the aboratory data, and the combined data by the method of least squares. ssuming a relationship of the form $k = bV^m$, the following were obtained:

For field data

$$k = 0.020\ V^{-1.51} \tag{6}$$

For laboratory data

$$k = 0.029\ V^{-1.54} \tag{7}$$

For all data

$$k = 0.024\ V^{-1.51} \tag{8}$$

The close agreement between the above equations suggests that $= 0.024\ V^{-3/2}$ can be used as a good approximation for both laboratory nd field observations. Since the type of bottom material represented n the equations (see Fig. 8) ranged from 1/4 inch pea gravel through and to smooth concrete, the type of bottom apparently is not as nportant as the velocity in determining the value of k.

Substituting the value of $k = 0.024\ V^{-3/2}$ into equation (5) gives he following relationship for the computed mean longshore velocity:

$$V_c = \left[\left(\frac{1}{4x^2} + y\right)^{\frac{1}{2}} - \frac{1}{2x}\right]^2 \tag{9}$$

here

$x = (108.3\ Hi\ \cos\alpha)/T$

nd $y = C\ \sin\alpha$

As an aid in computing longshore currents, equation (9) is eproduced in the form of an alignment chart in Fig. 9. This chart ives the mean longshore current in feet per second, when the breaker eight in feet, the period in seconds, the beach slope in per cent d the angle of breaker approach in degrees are known.

Using equation (9), the longshore current velocity V_c was computed r all of the field data listed in Putnam, et al (1949), and for the

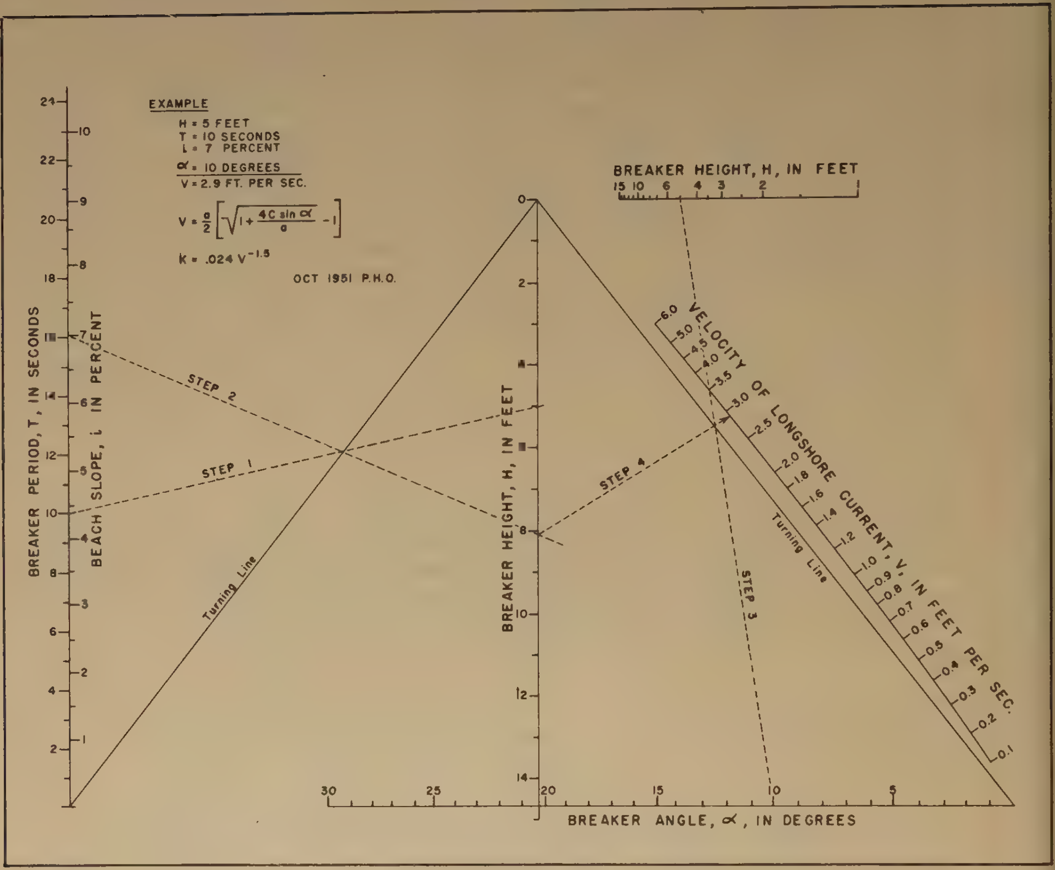

Fig. 9. Alignment chart for the computation of longshore current. Procedure: (1) lay straight edge from appropriate T to H and determine intersection with turning line; (2) turn straight edge about intersection to i, and determine intersection with H scale; (3) determine intersection on second turning line between H and α scale; (4) align intersections of H scale and second turning line and read velocity.

1950 observations at Torrey Pines and Pacific Beaches. The relative error in percent, $E = 100\,\frac{V_c - V_o}{V_o}$, between the calculated and the mean observed velocity was then computed for each series of observations, and the values of E classified. From the classified values of E the standard deviation of the errors (or standard error) σ_E, was obtained by a relationship similar to equation (2).

σ_E was computed for (a) field data having an observed mean longshore current velocity above 0.1 feet per second, and (b) field data having a mean velocity above ½ foot per second. The standard error for these two cases was 54% and 41%, respectively.

In the previous section on the variability of longshore currents ; was found that the average coefficient of variation, C_v, for case) was 91%. The average coefficient of variation is not directly mparable with the standard error. However, the question can be ked, "How many individual measurements of current, N, must the mean locity be based on in order that the average coefficient of variation equal to the standard error obtained by computing the velocity from uation (9)?" By letting σ equal 91% and S equal 41% in equation) we find that N equals approximately 5 observations. Thus the errors predicting mean currents above $\frac{1}{2}$ foot per second from equation (9) e comparable to the error of estimating the mean velocity from the an of approximately 5 measurements.

Comparison of the values of the coefficient of variation and the andard error suggest that the number of measurements, N, must be eater than 5 for mean longshore velocities below $\frac{1}{2}$ foot per second, the two errors are to be comparable. Also, to avoid station bias ee Fig. 7), the measurements should be obtained from many different ations scattered along the beach.

ACKNOWLEDGMENTS

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OCCURENCE AND IMPORTANCE OF BACTERIA IN INDONESIAN WATERS [1]

by

CLAUDE E. ZOBELL [2]

The Danish Deep Sea Round the World Expedition 1950—1952 under the leadership of Dr. Anton Fr. Bruun has afforded opportunities to learn much about the sea and its life in the vicinity of Indonesian islands. This information will be published eventually in the reports of the *Galathea Expedition*. In the meantime this summary of observations on the bacterial flora of this unique oceanic area, coupled with comments on the significance of bacterial activities, is prepared for the Journal for Scientific Research at the request of the Editor-in-Chief, Ir. G. Broersma, M. I. A. S.

The oceanic shelf connecting Sumatra, Java, Malacca, Borneo, and adjacent islands has been described by Kuenen (1950) as being the most extensive on earth, its area exceeding 2.000.000 km^2. Indonesian waters are characterized by marked irregularities in bottom topography that features young mountains, island arcs, and deep depressions. It is a strongly seismic area (Umbgrove, 1938), although devastating shocks are of rare occurrence. Among the more noteworthy depressions are the Java Trough and the Weber Deep, each exceeding 7.000 meters in depth in many places. For further information regarding bottom topography and other oceanographic conditions in Indonesian waters the reader is referred to van Riel (1934) and others who participated in the work of the *Snellius* Expedition to the East Indies. The Royal Danish Navy *Galathea* made it possible to collect for the first time samples from the bottom of these depressions for bacteriological and other types of examination.

The R. D. N. Galathea.

The R. D. N. *Galathea* is a 1630-ton frigate converted for studying the deep-sea floor around the world. It is 80 meters long and has a draft of 3 meters when loaded. Its two 1.000—horsepower Parson steam turbines provide for a cruising speed of 12 knots, with so little vibration that a high power microscope could be used while the ship was underway. Electric power for the motors to drive the winches, for lights, and for other auxiliary purposes is produced by two 100-horsepower reciprocating steam engines, one 100-horsepower Diesel, and one 400-horsepower Diesel engine. Though economical to operate, the latter created so much vibration throughout the ship that it was generally difficult or impossible to use a high power microscope while the big Diesel engine was running.

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[1] Contribution from the Scripps Institution of Oceanography, University of California, New Series No. 561. It is also a contribution from the Danish *Galathea* Expedition 1950 - 52.

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The ship is equipped with radar, loran, and other modern navigation aids. Locating great oceanic deeps and staying on position for several hours while collecting bottom samples required good navigation for which a high ribute is due to Captain Sven Gréve, chief navigator Commander Ivar Westergaard, and the other officers and men.

While in Indonesian waters the *Galathea* was manned by ten commissioned officers, 14 petty officers (many of whom have received commissions in the Royal Danish Navy since leaving Copenhagen in October 1950), 65 men, and an average of 12 scientific observers. The number of scientists aboard fluctuates, since some may leave or board the ship at principal ports of call. It is the general policy to have one or two scientists aboard from each country whose territorial waters are being investigated. For example, while sailing from Djakarta to Makassar, Indonesia was represented on the Expedition by Dr. J. D. F. Hardenberg and Mr. P. Ch. Veen of the Laboratory for the Investigation of the Sea.

Aboard for the purpose of keeping the people of Denmark and laymen elsewhere in the world informed regarding day to day discoveries was the well-known author and journalist Hakon Mielche and two professional photographers. Almost daily press releases were sent by wireless. Wire recordings of important events for radio broadcasts were sent by air express to Denmark from principal ports of call. Both still and motion pictures were taken of all significant discoveries. Such provisions for bringing the results of the Expedition to the *man on the street* back home, who is contributing to the support of this costly venture (Michelsen, 1951), sets a good example in public relations that might be copied to advantage by others.

Among the specialized equipment on the *Galathea* is the famous dredging cable, which makes it possible to collect samples of bottom deposits from the deepest parts of the ocean. In order to provide sufficient tensile strength to support itself as well as a load dredged from the sea floor, a special tapered cable or wire rope was constructed. The diameter of the cable increases from 9.3 mm for the first few thousand meters to 21.8 mm for the final thousand meters. The dimensions of the cable are as follows :

Section number	Length/meters	Diameter millimeters
1	3.600	9.3
2	1.750	11.6
3	770	13.2
4	1.330	14.7
5	1.730	17.1
6	1.080	19.6
7	980	20.2
8	1.060	21.8
Total length	12.300	

The weight of the 12.300 meters of cable when submerged in the sea was 7.900 kg. Since its tensile or breaking strength was 33.900 kg, it should support a pay load of 26.000 kg.

The cable was wound amidship by a winding winch on a spool or drum that was 225 cm long and 150 mm in diameter. The power winch for pulling the cable consisted of two 80 cm drums encircled four times by the cable held taut by the winding winch. When the power winch drums were made to revolve by a 200-horsepower motor, through a series of reduction gears, the cable was pulled.

Life at great depths.

Virtually every time that appropriate collecting gear was lowered into the sea by means of the great *Galathea* cable, it brought to the surface samples of historical scientific significance, since so little is known regarding conditions in the deep sea especially at depths exceeding 6.000 meters. Prior to the *Galathea* Expedition the greatest depth from which living bacteria had been recovered was 5.800 meters. Accounts of finding higher organisms at such depths were inconclusive. In fact, some scientists reasoned that the high hydrostatic pressure of water at great oceanic depths, coupled with the low temperature, lack of food in the dark deep waters, and other adverse conditions combined to make life impossible. Therefore it was with unusual interest that viable bacteria were recovered from the bottom of depressions exceeding 7.000 meters in Indonesian waters.

On 3 September 1951 a sample of mud was hauled to the surface from a depth of 7.200 meters at Station No. 463 (10°16′ S Latitude x 109°51′ E Longitude) in the Soenda Deep of the Java Trough. Portions of the mud which had come into contact with neither air nor extraneous water during sampling procedures were aseptically removed for bacteriological analysis. Examination of stained smears with a phase microscope providing a magnification of 980x revealed the presence of more than a million bacteria per gram. While such observations established the presence of large numbers of bacteria in deep-sea bottom deposits, it failed to prove whether the bacteria were alive or physiologically active on the sea floor where found. Proof for this required cultivating the organisms in a nutrient medium.

For the cultivation of the bacteria a medium of the following composition was employed :

Bacto-peptone	5.0 gm
Yeast extract	1.0 gm
Soluble starch	2.0 gm
Potassium nitrate	1.0 gm
Ferric phosphate	0.1 gm
Sea water	1000.0 ml

After sterilization in the ship's autoclave at 124°C, the reaction of the medium adjusted with 1/N sodium hydroxide was pH 7.7. The ship's physician, Commander Tage Fedderson, M. D., supervised the sterilization of the nutrient medium and otherwise assisted with the bacteriological analyses Acknowledgement is also due to Torben Wolff and Poul Jacobsen for help in handling the samples.

Within a few minutes after being brought to the surface, measured amounts of the deep-sea mud were inoculated into tubes of the nutrient medium for incubation under various conditions. There was little or no growth in tubes of the medium incubated at ordinary atmospheric pressure or at 30° C. However, there was appreciable growth of bacteria in tubes of the medium incubated in the ship's refrigerator at around 3° C, which approximated the temperature of the sea floor where the mud samples were taken. Far more bacterial growth occurred in tubes of medium incubated at 3° C in steel cylinders providing for a hydrostatic pressure of 700 atmospheres.

The pressure vessels, described in greater detail by ZoBell and Oppenheimer (1950), consist of 18—8 stainless type 303 steel cylinders, 30 cm long, having an outside diameter of 5.8 cm and an inside diameter of 3.4 cm. Each vessel was fitted with an „O" ring seal held in place by a cap 7.8 cm in diameter which, when screwed on by hand, made the vessel pressure-tight. From 20 to 24 small (10 x 50 mm) culture tubes, stoppered with No. 000 neoprene stoppers, were placed in each pressure vessel, after which the latter was filled with water. By means of a hydraulic pump connected to the closed vessels the desired pressure could be applied.

In general, pressure was applied to approximate that of the environment from which the samples were collected. The hydrostatic pressure of sea water increases with depth by about 0.1 atmosphere per meter. Thus at a depth of 7.200 meters the pressure is approximately 720 atmospheres. One atmosphere is equivalent to 14.696 lb/in^2, 760 mm Hg, 1.0332 kg/cm^2, or to 1.0133 bars. The pressure-depth gradient in the sea is affected only slightly by latitude, temperature, and salinity.

Confirming the results of ZoBell and Johnson (1949) and Oppenheimer and ZoBell (1952), it was found that the growth and physiological activities of bacteria from appreciable depths were affected by the hydrostatic pressure. From ten to a hundred times more bacteria in bottom deposits from the Java Trough reproduced at 700 atmospheres than at atmospheric pressure. This observation provides further evidence that the bacteria must be species that are indigenous to the deep sea. Many more bacteria were demonstrated in bottom deposits than in the overlying water. Representative findings at two stations are summarized in Table I.

Table I. *Minimum numbers of bacteria per gram wet weight of mud from Indonesian deeps that grew in nutrient medium incubated at different temperatures and pressures.*

Station number	463	492
Station location	10°16′ S × 109°51′ E	5°31′ S × 131°01′ E
Name of deep	Soenda in Java Trough	Weber in Banda Sea
Depth in meters	7.200	7.400
Date of sampling	3 September 1951	20 September 1951
30° C and one atmos.	10^2	10^3
30° C and 700 atmos.	10^3	10^4
3° C and one atmos.	10^4	10^4
3° C and 700 atmos.	10^6	10^6

Cultural counts, such as those summarized in Table I, must be regarded as minimal, since no one medium or set of cultural conditions could conceivably provide for the growth of all organisms present in mud samples. Similar results were obtained earlier on the *Galathea* Expedition on samples taken from the bottom of the Philippine Trench between 15 July and 14 August 1951. Some of the results (ZoBell, 1952) are summarized in Table II.

Table II. *Minimum numbers of bacteria per gram wet weight of mud from the Philippine Trench that grew at different pressures at 3° C.*

Station number	Water depth in meters	Cultures at 3° C	
		one atmos.	1000 atmos.
413	10.380	10^4	10^5
418	10.460	10^3	10^6
421	1.020	10^5	0
422	2.010	10^6	0
424	10.390	10^4	10^6

These data establish world's records for the greatest depth from which living organisms have been recovered and the highest hydrostatic pressure at which organisms have been cultivated. Incidentally, other world's records were established by Bruun's (1951) finding several animal phyla in the Philippine Trench at depths exceeding 10.000 meters, including 27 actinians, more than a hundred holothurians, five bivalves, three amphipods, five echiurid worms, and two species of tanaids, the latter being small crustaceans.

All of the animals appeared to be dead when they reached the surface. While changes in hydrostatic pressure attending their passage from the deep sea floor to the surface may have contributed to the death of the animals, there is a concurrence of opinion that the change in temperature was primarily responsible for the death of the deep-sea animals. The change in temperature was from near 3° C at the bottom of the Philippine Trench to about 30° C at the surface. In the Soenda and Weber Deeps the bottom temperature was near 3° C and about 26° C at the surface.

Just how many bacteria may have succumbed to changes in temperature and pressure as the bottom samples were hauled to the surface is indeterminate, but it is significant that many survived this transition. It is hoped to learn more about the pressure-temperature tolerance of organisms by investigating the physiology of cultures of barophiles isolated from great depths. The term *barophile* was coined by ZoBell and Johnson (1949) to characterize organisms that grow at high pressure.

Data inclued in Table II were selected to illustrate that bacteria from relatively shallow water, like those from surface sources, do not grow at high pressure characteristic of extremely deep water.

Food for deep sea organisms.

With the exception of the small amount of organic matter that may be synthesized by autotrophic bacteria that obtain their energy from the oxidation of methane, molecular hydrogen, sulfur, hydrogen sulfide, and certain other inorganic compounds, primary productivity in the sea is confined to the euphotic zone where sunlight provides energy for the formation of organic matter by photosynthetic organisms. This means that most organic matter is synthesized in the topmost few hundred meters of water. To what extent any of this organic matter or the organic remains of plants or animals of terrestrial origin reaches the deep-sea floor is problematical. The low organic content of many deep-sea bottom deposits suggests that relatively little organic remains of plants or animals reaches abyssal dephts. What then is the source of food for deep-sea organisms ?

Finding fragments of chitin or cellulose from surface-dwelling organisms indicates that some organic matter does reach certain oceanic deeps. This may be supplemented to a significant extent by bacteria, which are known to serve as a source of food for a good many types of marine animals (ZoBell, 1946). Besides the bodies of autotrophic bacteria, which are probably of minor importance in the food cycles in the sea, heterotrophic bacteria synthesize cell substance by utilizing dissolved and other kinds of organic matter commonly found in sea water, the average content being of the order 5 mgm/L. Although certain marine animals may be able to utilize colloidal organic matter (Fox, 1950), bacteria stand more or less alone in being able to assimilate dissolved organic matter.

By their assimilation of dissolved, colloidal, detrital, or other forms of organic matter with the conversion of from 30 to 40 percent of it into nutritious cell substance, bacteria may serve as an important source of organic nutriment for marine animals. This may be particularly true in the deep sea where dependence for the influx of dissolved or suspended organic matter is upon the movement of water masses. Much more work will be required to appraise the part played by bacteria in food cycles in the sea, but it is of interest to find at the greatest known depths sufficient bacteria to contribute to the nourishment of bottom-feeding animals. It is equally interesting to note that most of the animals found on the deep-sea floor are types adapted to feed on small particles like bacteria.

Biochemical activities of bacteria.

Bacterial cultures recovered from the deeps described in Table I and II have been shown to be physiologically versatile as indicated by various biochemical activities. Ammonia production in the culture medium, demonstrated by Nessler's reagent, showed that peptone was deaminized. The disappearance of starch, demonstrated by a negative iodine reaction in certain cultures, showed that this complex carbohydrate is hydrolyzed. The disappearance of nitrate and the formation of nitrite in the culture medium indicated the reduction of nitrate by certain deep-sea bacteria incubated under conditions designed to simulate their natural habitat. The respiration of aerobic bacteria often resulted in the depletion of dissolved oxygen from sea water medium enriched with organic nutrents.

Earlier investigations, reviewed by ZoBell (1946, 1947) have demonstrated in marine bottom deposits collected from different parts of the world the occurrence of bacteria that are capable of attacking virtually all kinds of organic compounds, including such complex substances as agar, cellulose, chitin, humus, and lignin. Such organisms are believed to play an important part in the mineralization of organic matter in the sea with the formation of carbon dioxide, ammonia, sulfate, phosphate, and other plant nutrients.

A few specialized bacteria oxidize ammonia to nitrite. Others oxidize nitrite to nitrate. Under certain conditions nitrate or nitrite may be reduced by marine bacteria. Nitrogen-fixing forms have been found in the sea. Also present in marine environments are bacteria that modify sulfur compounds in various ways. Some oxidize sulfides. Commonly found in bottom deposits are large numbers of bacteria that reduce sulfate with the formation of hydrogen sulfide. The biochemical activities of sulfate-reducing bacteria are often responsible for the vitiation of water in stagnant basins.

By catalyzing the transformation of both organic and inorganic constituents of marine mud, bacteria appear to be the principal dynamic agencies that affect its hydrogen-ion concentration (pH) and oxidation-reduction potential (Eh). The pH as well as the Eh is believed to have a pronounced effect on the composition, chemical reactivity, diagenesis, color, biological population, geochemistry, and other properties of recent sediments.

By splitting nitrogen, sulfur, phosphorus, and oxygen from the organic remains of plants and animals deposited in the floor of shallow sea, anaerobic bacteria tend to increase the percentage composition of hydrogen and carbon, thereby producing substances which are more petroleum-like than the original organic matter. Methane is produced by a good many marine bacteria, and there is some evidence for the formation of higher hydrocarbons by certain bacteria which may influence the origin of oil in many ways (ZoBell, 1950).

Although primarily beneficial in the economy of the sea, certain biochemical activities of marine bacteria are harmful. Included in this category are those that infect living plants or animals, cause the decomposition of fish or other food products from the sea, promote the deterioration of cordage or wood, or contribute to the corrosion of concrete and iron structures.

It is the long range objective of the marine microbiologist to learn everything possible about the occurrence, characteristics, and activities of bacteria and allied microorganisms in the sea with a view to gaining a fuller understanding of the oceans of the world. Some of this knowledge may be applied to the control of certain harmful activities while taking full advantage of those bacteria that are beneficial to man.

Results obtained on the *Galathea* Expedition have contributed much to our knowledge of marine microbiology, and it is to be expected that further contributions will be forthcoming from a detailed study of unique cultures collected in Indonesian waters.

Acknowledgement.

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A special debt of gratitude is due the the people of Denmark who, as pointed out by Michelsen (1951), provided the funds for the *Galathea* Expedition that has contributed so much to man's knowledge of the deep sea and to a fuller understanding of people and their problems in far away places.

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WINTER POPULATION OF PINNIPEDS ABOUT GUADALUPE, SAN BENITO, AND CEDROS ISLANDS, BAJA CALIFORNIA

BY GEORGE A. BARTHOLOMEW, JR., AND CARL L. HUBBS

Between January 27 and February 10, 1950, as guests of Joseph W. Sefton, Jr., a scientific party, including the authors, visited Guadalupe, San Benito, and Cedros islands aboard the Research Ship *Orca* of the Joseph W. Sefton Foundation. The primary purposes of this trip were to determine if there still exists on Guadalupe Island a population of the Guadalupe fur seal, *Arctocephalus townsendi* Merriam, of which a single adult male had recently been seen on San Nicolas island, California (see below), and to study further the numbers and biology of all the pinnipeds on these Baja California islands. Records were made of all individuals seen at sea and censuses were taken of the pinniped populations on each island. These observations yielded a hitherto unavailable picture of the winter population in this area.

No harbor seals, *Phoca vitulina geronimensis* Allen, were seen on any of the islands, although according to Goldman (1951: 407) they still occur on Guadalupe Island. We have found no confirmation of this report.

GUADALUPE ISLAND

A fortunate combination of good weather, co-operative personnel and continuous access to boats well adapted to our purposes made it possible to examine, with considerable thoroughness, the coastal areas of Guadalupe Island, particularly on the south and east sides (Fig. 2).

On the *Orca* we completely circumnavigated this oceanic island, cruising close to the shore and recording the numbers, kinds, and locations of all marine mammals seen. Twice one of us (Bartholomew) examined every nook and cranny of the east coast between Melpomene Cove and a point six miles north of South Bluff in one of the *Orca's* motor launches, skillfully operated by A. A. Allanson of the Scripps Institution of Oceanography. Four days were spent ashore, two and a half at West Anchorage and along the adjacent coast both north and south, one along the southern part of the east coast, and a half day on the beaches south of Pilot Rock. Outer Islet was visited twice and the area about the anchorage in Melpomene Cove was under almost continuous surveillance. We feel that the counts resulting from these efforts rather accurately indicate the numbers and kinds of Pinnipedia on Guadalupe Island during the visit.

Zalophus californianus (Lesson). California sea lion.—For the past half century, during which counts have been made at irregular intervals, the population of sea lions on Guadalupe Island has always been small, in comparison with the great concentrations about the islands and rocks nearer the mainland. Townsend (1899) reported that the only sizable aggregation which he saw on circumnavigating the island in June, 1892, was a group of about 30 hauled out on Outer Islet. As a result of his search for pinnipeds about Guadalupe in June, 1897, Thoburn (1899) similarly indicated that the only large group of sea lions found was a herd on Outer Islet consisting of 10 bulls, 50 cows, and 31 pups. After a week's circumnavigation of the island, in July, 1922, Anthony (1925: 304) reported that ". . . one rookery of a dozen was found and a few scattered individuals along the shores that might have made the Guadalupe count as much as 50 animals."

During the period of our visit the *Zalophus* population, although larger than previously reported, was still of modest size. In addition to five individuals seen at one time or another off the east and west sides of the island, sea lions were found in only two areas. The largest single group hauled out regularly on the ledges along the west and south sides of Outer Islet. It contained a minimum of 134 animals, largely adult females and young males; only 3 adult males and 12 yearlings and young-of-the-year were seen. The other concentration of *Zalophus* was near the north end of Guadalupe: On February 3, a half dozen were observed near Pilot Rock and about 20 otariids, presumably *Zalophus*, were seen from a distance about one-fourth mile off the north shore.

The observed scarcity of yearlings and young-of-the-year in the herd on Outer Islet is what one would expect in a stable or decreasing population. The small size and stability of the *Zalophus* population of Guadalupe is of particular interest because of the availability of an extensive and relatively unexploited habitat apparently suitable for sea lion occupancy. The abandoned fur seal rookeries harbored not a single *Zalophus* at the time of our visit. Clearly, the small size of the population is not attributable to any inadequacy of the hauling grounds. Nor can we plausibly attribute the low numbers to lack of food, for we have found the local waters to abound in fishes. Neither can we assume that the sea lions' scarcity is related to the abundance of other pinniped species, for the numbers of fur seals have long since been reduced to insignificance and the cohabitation of elephant seals (now abundant) and sea lions is attested by their free sharing of rookeries on San Benito Islands (see below) and on Los Coronados and San Nicolas islands to the northward.

The long persistence and integrity of the Outer Islet colony, despite its small size and the very limited hauling ground (a narrow shelf on a nearly vertical face), is attested by the long record of a moderate proportion of albinistic individuals in this population. These "albinos" have been well known to the biologists who have visited the island from time to time during the past quarter century. Some were seen by us. Others are shown on a color photograph taken by George E. Lindsay in 1948. Lewis Wayne Walker (personal communication) estimates that the "albinos" have constituted about ten per cent of the small population on each of his several visits during the past twenty years. He further states that William E. Clover, who rediscovered the fur seals on the island, and Dr. Harry Wegeforth, when President of the San Diego Zoological Society, and also Luis Camillo and others, often spoke of seeing albinos on the south side of Outer Islet repeatedly from 1926 to about 1935.

Why the sea lions on Guadalupe Island have failed to take over the abandoned fur seal rookeries is a mystery, especially since the sea lions on the San Benitos now occupy all available sites, some of which originally must have been utilized by the fur seals that, as Anthony (1925: 308) has shown, once abounded there.

A possible explanation for the scarcity of sea lions on Guadalupe is that some of the environmental conditions on this truly oceanic island, which rises abruptly out of very deep water, do not satisfy the full needs of this essentially coastal animal. The other islands inhabited by *Z. californianus* are surrounded by the continental shelf.

Arctocephalus townsendi Merriam. Guadalupe fur seal.—The discovery during the summer of 1949 of an adult male of *Arctocephalus townsendi* on San Nicolas Island, California (Bartholomew, 1950) led us to expect that a population of this once wide-spread species might persist on Guadalupe Island, which was its last major holdout (Starks, 1922; Anthony, 1925; Townsend, 1931). It was on this island that the species was rediscovered in January, 1926, after it had been long thought to be extinct.

An intensive search for *Arctocephalus* was therefore made about Guadalupe Island throughout our stay. In this effort we were materially aided by testimony furnished to Joseph W. Sefton, Jr., and one of us (Hubbs) by Harry Fisher, just before his death. Fisher was the partner of William E. Clover and the fellow rediscoverer of the fur seal.

An entire day was spent ashore in a minute examination of the stretch of coast identified by Fisher as the area where the fur seal was rediscovered and where he thought that Clover, in 1928, captured the two male specimens that were brought to the San Diego Zoo

(Huey, 1930; Bartholomew, 1950). This site was given as being on the east shore about four miles north of the south end of the island, and as being marked by a double point with a small rock pinnacle off the southerly tip. Such a point was found at the indicated position. Between the points there was a cave with a covered entrance corresponding to the description given by fishermen (Fisher, Clover, and Luis Camillo) of the cave which the fur seals entered and where the Zoo specimens were netted.

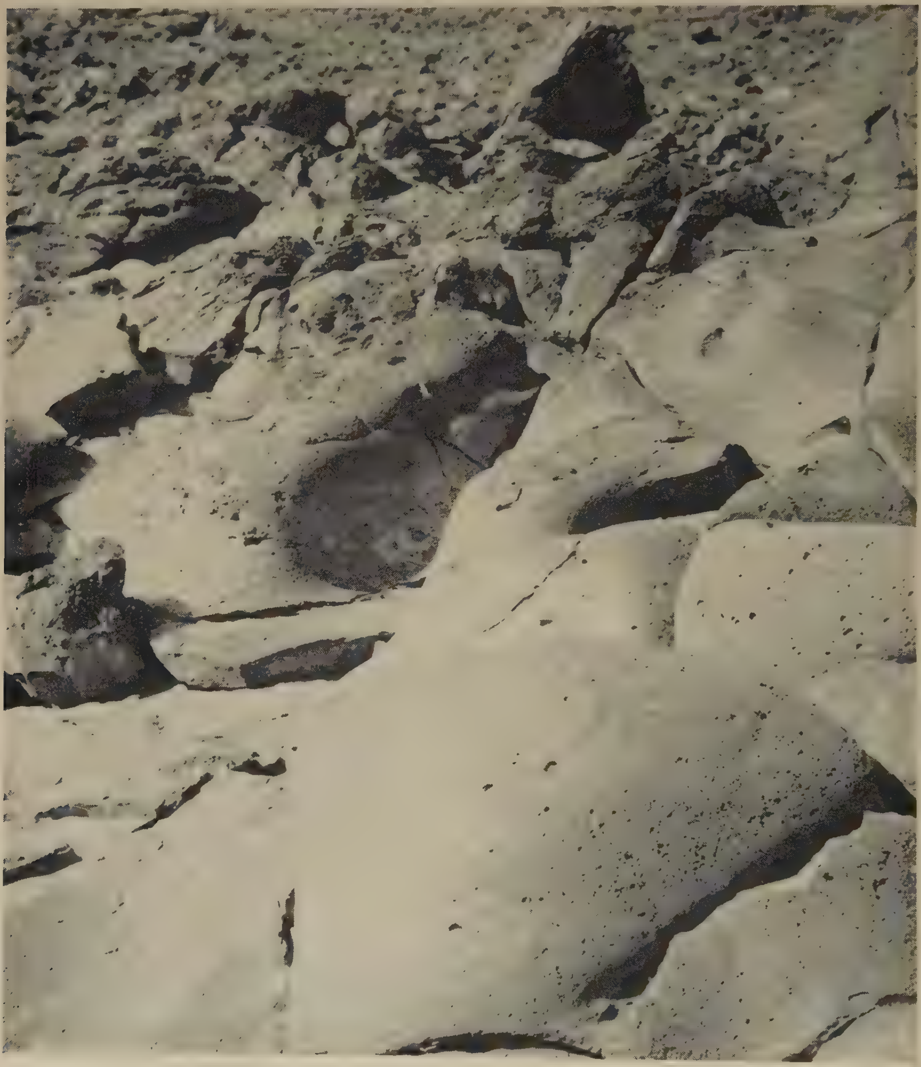

PLATE I

The inland edge of an abandoned fur seal rookery on the south end of the east coast of Guadalupe Island, showing the polish imparted to the rocks by the movements of generations of fur seals, and the abrupt transition from polished to unpolished rock.

From the testimony of Fisher and others it seems highly probable that a small residual population existed along this section of the east coast of Guadalupe Island for several years following the rediscovery in 1926. Fisher recalled having counted 31 here and he said that neither he nor Clover found any elsewhere. He admitted having shot two, but did not disclose their disposition. Lewis Wayne Walker, who made several trips to Guadalupe Island with Dr. Harry Wegeforth following the capture of the two specimens in 1928, recalls having seen individual fur seals several times at the supposed point of rediscovery, but he thinks that the observations were made only about one-third the way down the east coast from the north end of the island.

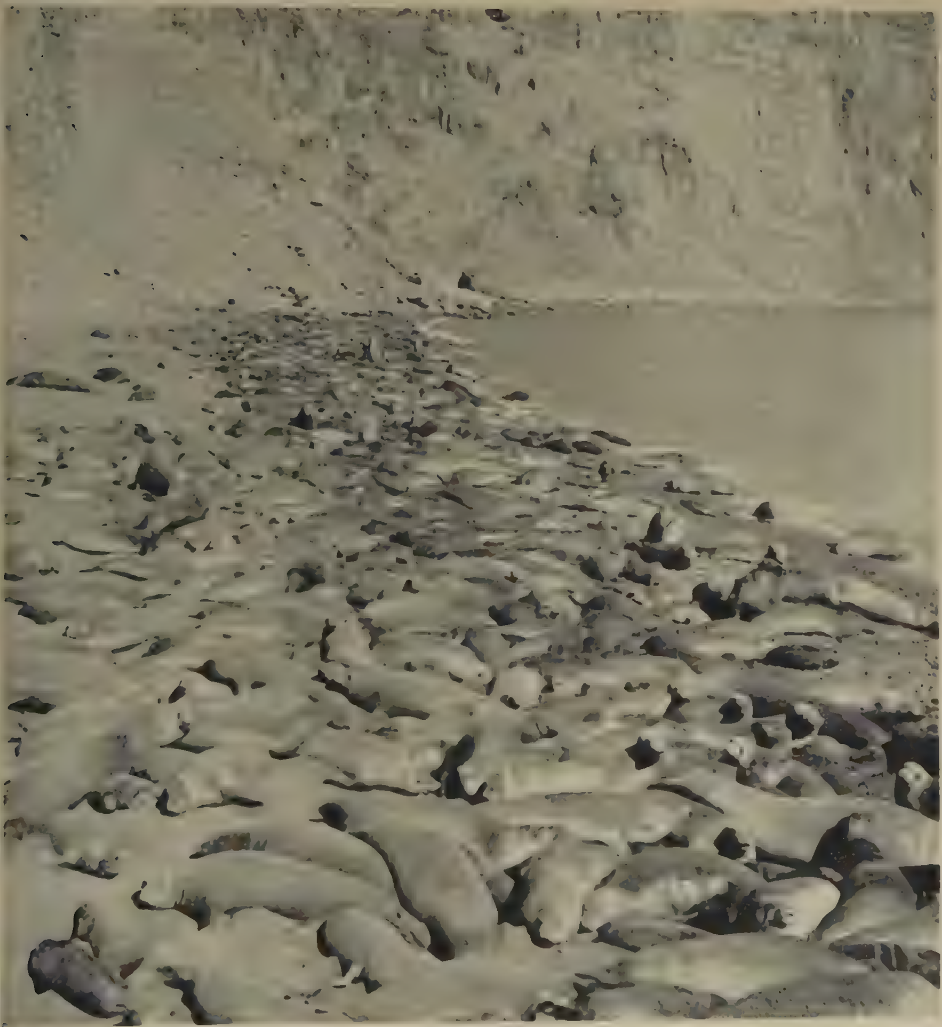

PLATE II

A view of part of the herd of elephant seals on the beach south of Pilot Rock, Guadalupe Island.

The long-abandoned fur seal rookery at West Anchorage was carefully watched for two and a half days and several visits were made to the other abandoned rookeries, at Melpomene Cove and on the east coast several miles north of South Bluff. In addition, repeated searches were made from a launch elsewhere along the east shore and a watch was maintained as the *Orca* cruised along the northern and western as well as along the eastern shores.

None of these efforts yielded any indication of the presence of fur seals on Guadalupe Island either now or in the recent past. The old fur seal rookery at West Anchorage, marked not only by rocks polished to a high sheen by generations of fur seals (Pl. I), but also by crumbling stone huts built in the days of the Russian fur trade (Anthony, 1925), is now occupied only by a small herd of elephant seals. The rookeries at Melpomene Cove and on the east coast, also marked by polished rock, remain completely unoccupied and do not appear to have been recently inhabited by any pinnipeds.

Since we were unable to search the north and northwest parts of the island with the same degree of attention that we devoted to the east and south coasts, it would be presumptuous to state categorically that during our visit there were no fur seals on Guadalupe. We can say with considerable confidence, however, that there were none on the west side of the island south of a point three miles north of West Anchorage and none on the south or east sides of the island. It is possible that the adult male seen recently on San Nicolas Island (Bartholomew, 1950) was the last living remnant of a once flourishing tribe.

Mirounga angustirostris (Gill). Northern elephant seal.—Since the rediscovery of the northern elephant seal on Guadalupe Island in 1892 (Townsend, 1899), the population of this species has been of interest to mammalogists and conservationists. What little was known of the population increase from 1892 to 1929 was summarized by Huey (1930). Although a number of biologists have since visited the island no further censuses have been published, except the 1948 count of Fitch and Wilson (1949).

Despite the meagerness of the data and despite the circumstance that the various counts have been made at different times of the year, and have thus covered considerable seasonal fluctuations in the number of animals on the island, the available censuses indicate a definite and spectacular increase over the last decade or two (Fig. 1). The increase has been so marked that the errors in sampling do not obscure the basic picture.

The northern elephant seal was brought to the brink of extinction by commercial hunting. When the population reached such a low point (probably less than 100 individuals) that hunting was no longer profitable, commercial exploitation, of course, stopped. Before the population had again become large enough to be economically attractive the Mexican Government extended protection, under which the small herd has prospered. The species, when it was accorded almost complete protection from the one agent, man, which nearly caused its extermination, multiplied rapidly in the unoccupied niche to which it was adapted. Neither poaching for "trimmings"—male genitalia dried for export to China for the preparation of an aphrodisiac drug (Beebe, 1942)—nor the occasional wanton shooting by visiting fishermen (an instance of which we observed at Melpomene Cove in 1950) has been effective in preventing the increase of the population.

The conditions for population increase seem to have been almost as optimal as in a laboratory study, in which a small known number of organisms is introduced into a most favorable environment. The growth curve shown by the population from 1892 to 1950 (Fig. 1) indeed approximates the lower part of the logistic curve to which the growth of most experimental populations can be fitted. There was a slow initial increase in the years following 1900, but as the population grew the rate of increase became progressively greater. During the last two decades the numbers have increased prodigiously. There are no indications, however, that the curve has approached its point of inflection. If conditions remain as favorable as they now are, we can expect that the population of the species will continue to build up at an increasing rate and will not approach its asymptote until it has increased several-fold. The species has only begun to expand into its previously occupied range and still has an enormous, largely unoccupied habitat available, in California as well as in Baja California.

In any event, the more than 4500 elephant seals that were present on Guadalupe Island during the period of our visit represent by far the largest population of this species that has ever been recorded from the island. Plate II offers graphic evidence of the abundance of these animals on one of the beaches.

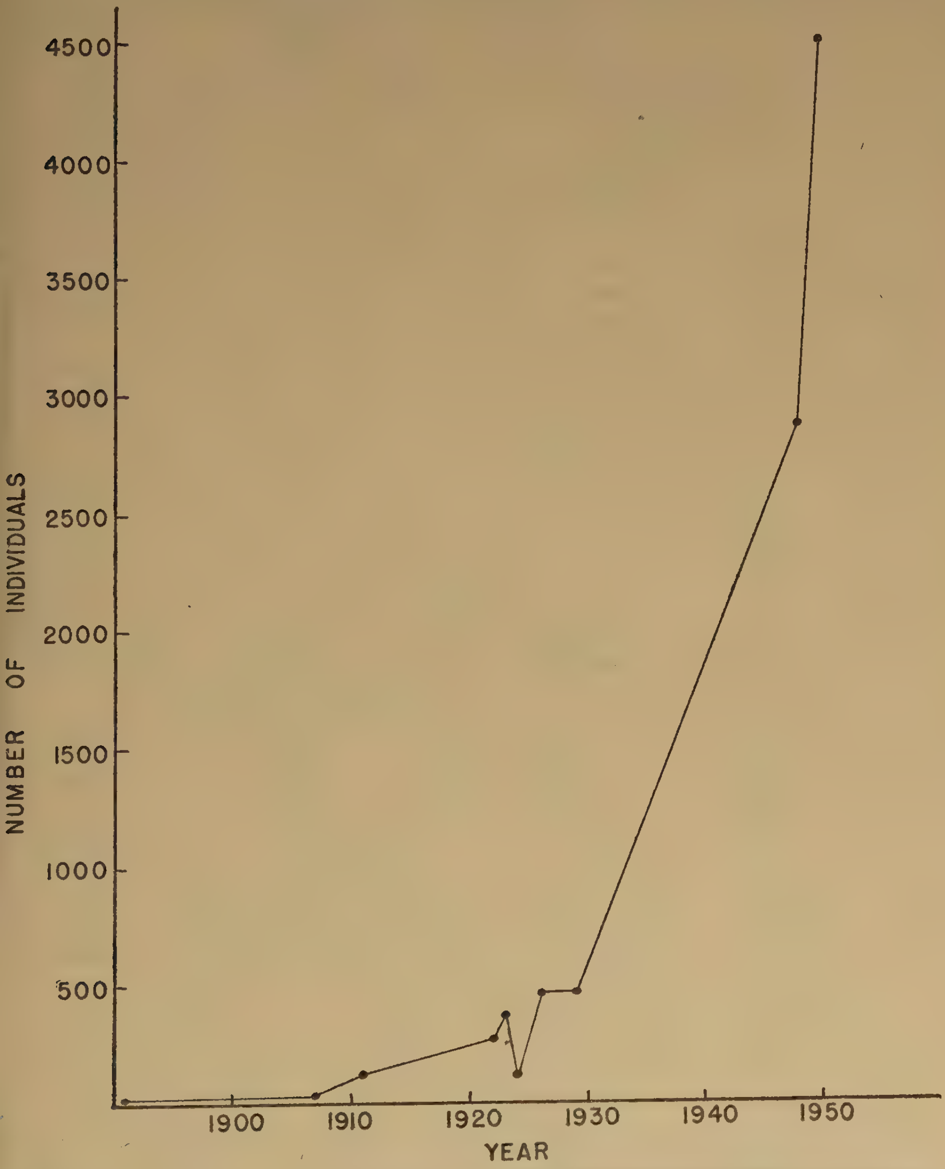

Fig. 1.—The growth of the Guadalupe Island elephant seal population. The data for the years prior to 1930 are from Huey (1930) and the data for 1948 are from Fitch and Wilson (1949).

Associated with this increase in numbers has been a change in the distribution of elephant seals on Guadalupe Island. During the early years of the present century, the animals were found only on the beach south of Elephant Rock. Now, at least during the winter, as can be seen from Fig. 2 and also from the figure in the paper of Fitch and Wilson (*op. cit.*), the animals are scattered widely along both east and west sides of the northern part of the island and a sizable herd is established at West Anchorage.

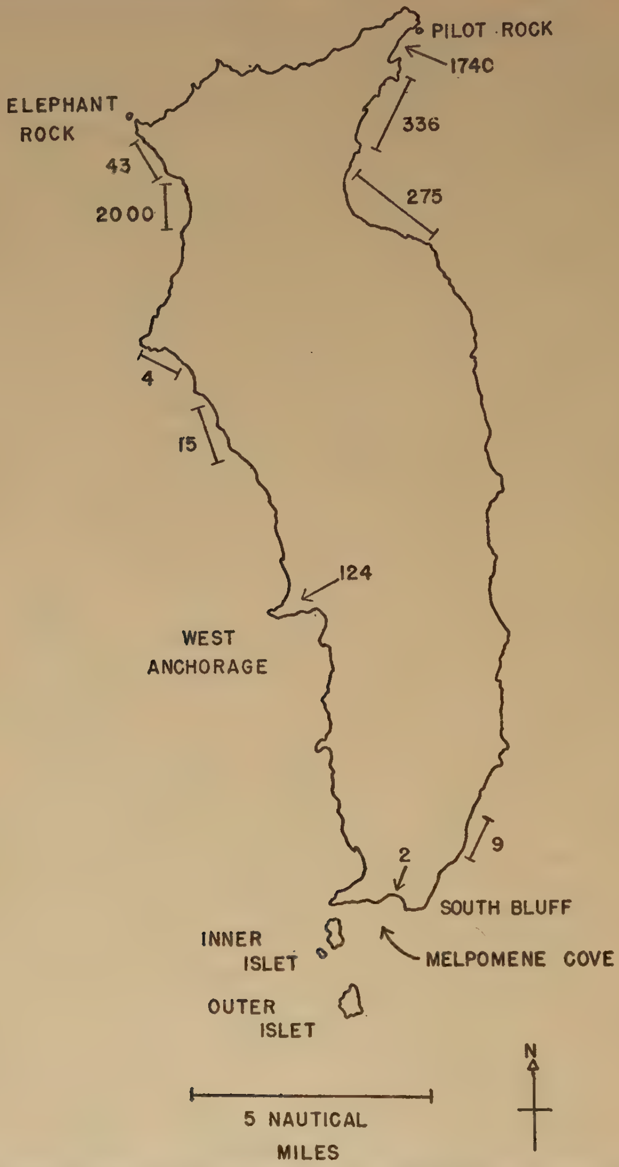
PILOT ROCK
1740
336
275
ELEPHANT ROCK
43
2000
4
15
124
WEST ANCHORAGE
9
2
SOUTH BLUFF
INNER ISLET
MELPOMENE COVE
OUTER ISLET
5 NAUTICAL MILES
N

FIG. 2.—The distribution of elephant seals on Guadalupe Island during the last week of January and the first week of February, 1950. The number of animals on the beach south of Elephant Rock was approximated by a rather distant observation. The number on the beach south of Pilot Rock was determined by counting and by analysis of a series of photographs, of which Pl. II is an example.

SAN BENITO ISLANDS

The abundance of pinnipeds on the San Benitos at the time of our visit was well-nigh unbelievable. Over long stretches of coast, every available bit of beach

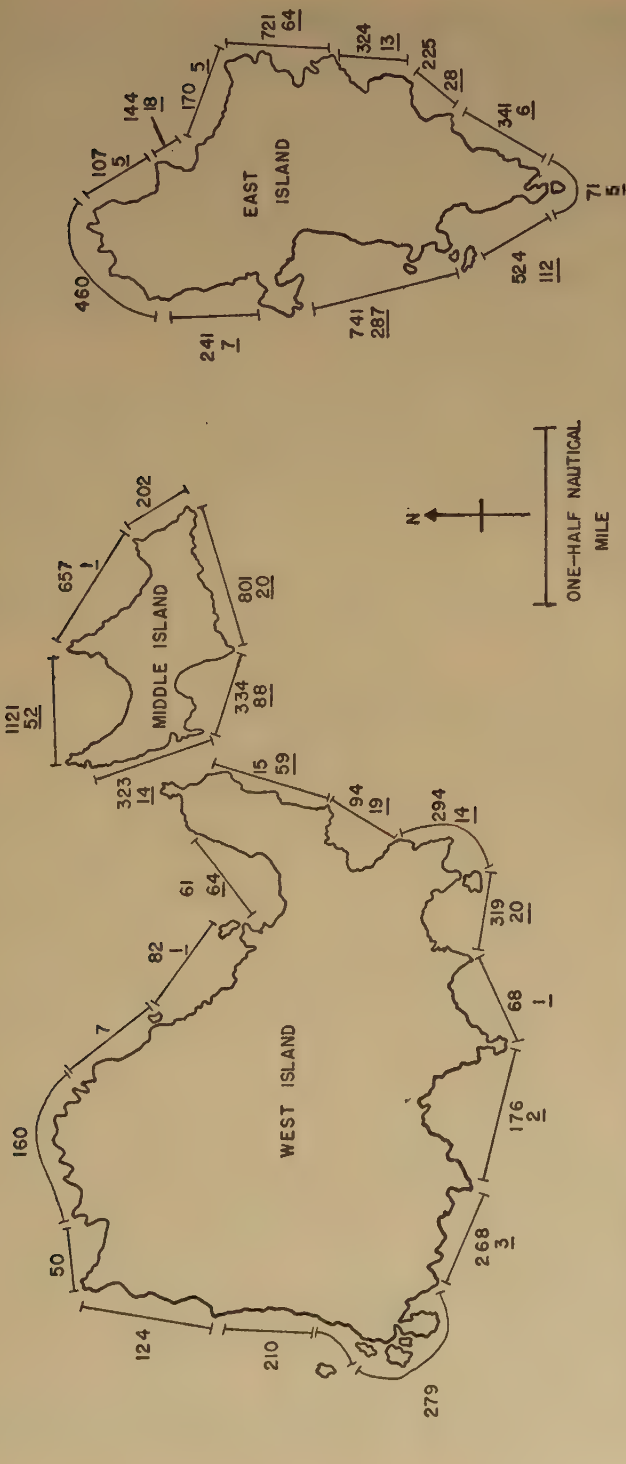
EAST ISLAND
MIDDLE ISLAND
WEST ISLAND
N
ONE-HALF NAUTICAL MILE
721 64
324 13
225 28
341 6
71 5
524 112
741 287
241 7
460
107 5
144 18
170 5
202
657 1
1121 52
801 20
334 88
323 14
15 59
94 19
294 14
319 20
68 1
176 2
268 3
279
210
124
50
160
7
82 1
61 64

FIG. 3.—The distribution of pinnipeds on the San Benito Islands on Feb. 5, 1950. The underlined numbers indicate elephant seals. The numbers without underlining indicate California sea lions.

and rock was occupied by elephant seals or by sea lions, and groups of the latter were congregated on barren areas 100 feet or more above the water and as far as 150 yards from the shore.

On February 5, with the help of A. A. Allanson and Frederick H. C. Taylor of Scripps Institution, we circumnavigated each of the three small islands of the San Benitos group in a launch. We cruised inside the kelp and just outside the surf, examining every foot of the shore and counting on hand-talley counters all pinnipeds seen in the water and on the land. The numbers in each of the coves, beaches, and headlands were recorded on charts. Since the numbers (Fig. 3) represent animals actually seen, the totals are minimum figures for the pinniped population of the San Benitos.

Zalophus californianus (Lesson). California sea lion.—In the first part of February, 1950, the San Benito Islands were literally overrun with sea lions. Despite their magnitude, the numbers shown in Table 1 and Fig. 3 suggest only feebly the overwhelming abundance of these animals, which swarmed like huge maggots over and around all three islands.

We counted 9714 individuals of *Zalophus* on the three small islands (Table 1) and there can be little doubt that the population at the time of our census was actually well in excess of 10,000. An appreciation of the large size of the San Benitos *Zalophus* population in February, 1950, can be gained from the fact that it was over three times as large as the largest total summer population of this species indicated for the entire State of California by the censuses of the California Division of Fish and Game from 1927 to 1948 (Bonnot and Ripley, 1948).

During the last half century the sea lion population of the San Benitos has not always been at this high level. In March, 1911, only 1700 were found there (Townsend, 1916) and in August, 1922, the population was estimated at 400 (Anthony, 1925).

The size of the sea lion population of the San Benitos is of particular interest because in 1939 an American company killed a large number of the animals on the islands for conversion to dog food. The exact number of animals slaughtered cannot now be determined, but apparently it was very great. Beebe (1942) stated categorically that all sea lions on the San Benitos were killed, but the San Benitos lighthouse keeper, in a conversation with Mr. George E. Lindsay, of the *Orca*'s scientific party, estimated that about half of the animals on the islands were killed.

According to Kenneth E. Stager (personal communication), who visited the islands in March, 1940, there were at that time fewer than 2000 sea lions on East Benito—less than half as many as when we visited the same island in February, 1950. At the time of our visit the sea lions appeared to have largely recovered from the killing and there is reason to believe that the population is still increasing.

Lindsay, who collected plants on all three of the San Benitos, pointed out to us vegetational evidence that the sea lion population of the islands was at a higher level than it had been in the years immediately preceding 1950. One of the conspicuous plants on the San Benitos is a soft cactus, *Mammillaria neopalmeri*, which, over considerable areas, particularly on Middle Island, has established itself as the dominant plant. In the San Benitos, the sea lions move 150 yards or more inland to congregate in groups of several hundred individuals. In their movements overland, the sea lions have denuded the ground of most of the plants and have, over considerable stretches of terrain, worn the spines off the *Mammillaria*. Recently in some areas many of the cacti have been uprooted. Under such mechanical abuse, the cacti could never have established themselves as seedlings. Therefore, at the time when they did establish themselves in areas near the beaches, the sea lion population must have been much smaller than it now is.

That the San Benitos sea lion population is still expanding is further indicated by the observed preponderance of young animals. At least three out of four and possibly four out of five of the sea lions in the San Benitos were less than three years old and the large majority were less than one year old.

Although extremely different in structure, the sea lion populations on Guadalupe and on the San Benitos agreed in the conspicuous absence of adult males. Of the 9714 sea lions which we counted on the San Benitos, only 11 were identified as adult males. Similarly on July 29, 1949, when Dr. J. L. McHugh estimated the population of Middle Island alone as 5000 (our count for this island was 3438) he observed very few adult males (personal communication). At no time during our passages at sea or on any of the islands visited in the winter of 1950 did we see adult males except as single individuals.

It seems probable that the adult males leave the vicinity of the San Benitos after the breeding season. That they may migrate northward as far as California seems possible. A very high proportion of adult males has been observed in non-breeding aggregations in that state. Thus on April 22, 1950, Bartholomew estimated that fully 80 per cent of the 956 sea ions on a sandy beach on San Nicolas Island were adult males. On July 9, 1949, there were on this same beach 164 sea lions, nearly all males. The overwintering population of sea ions on a beach in Monterey County south of Point Sur, with numbers estimated by Hubbs as high as 1800 and by others still higher, consists largely of adult males of this species, with few Steller sea lions. Fry (1939) has indicated the possibility of a winter movement of sea ions into California from Baja California.

TABLE 1.—*Pinniped populations in January and February, 1950, on certain islands off the northern coast of Baja California*

DATE	PLACE	ZALOPHUS	MIROUNGA
Jan. 27–Feb. 3	Guadalupe	165	4,548
Feb. 4–7	San Benitos		
	East Island	4,069	550
	Middle Island	3,438	175
	West Island	2,207	183
	San Benito Totals	9,714	908
Feb. 7	Cedros	340	0
Total		10,219	5,456

Mirounga angustirostris (Gill). Northern elephant seal.—Prior to their commercial xploitation, elephant seals occurred in large numbers on the San Benitos, and these islands were perhaps the first outside of Guadalupe to be reoccupied by breeding colonies of his species as its numbers increased. Individuals and small groups have apparently been auling out on these islands for many years. Hanna (1925) reported that at least six were een in the islands as early as 1918. According to Williams (1941) the animals probably established themselves first on East Island.

At least since 1925 (Bancroft, 1932) the elephant seal has been present on the San Benitos n some numbers, although the size of the total population on all these islands apparently ad never been determined prior to our visit. In August, 1946, Hubbs saw at least five dead nd at least three live bulls on the north shore of West Island, and at least eleven live cows nd bulls on the west side of Middle Island. In March, 1948, there were elephant seals on all hree islands and "at West San Benito Island approximately 700 elephant seals were indiated by shore counts" (Fitch and Wilson, 1949). On July 29, 1949, J. L. McHugh (personal ommunication), on the basis of rather thorough observations, estimated the elephant seal opulation on Middle Island as 500. On February 4–7, 1950, we found 183 elephant seals on West Island, 175 on Middle Island, and 550 on East Island, bringing the total for the San enitos to a minimum figure of 908 (Table 1).

Elephant seals of both sexes and all ages were present at the time of our visit and breeding activities were being carried on with great vigor and enthusiasm on each of the islands.

CEDROS ISLAND

We did not completely circumnavigate Cedros Island, but on February 7 and 13, we cruised along the whole length of the east coast of the island close inshore. As the sea was calm and the visibility was excellent, we were able to examine the entire stretch of coast in detail. Despite mile after mile of beautiful smooth beach not a single elephant seal was seen and, aside from three California sea lions seen off Cedros Village on February 7, and 12 sea lions observed off the southern end of the island on February 13, no pinnipeds of any kind were seen except in a cove south of the North Lighthouse. Here, on February 7, we counted on the sandy beach 340 sea lions, including not more than fifteen adult males.

SUMMARY

In the last week of January and the first two weeks of February, 1950, on a trip to Guadalupe, San Benito, and Cedros islands, Baja California, aboard the Research Ship *Orca*, the authors made a census of the pinnipeds on each island. A careful, but completely unsuccessful, search was made for a possible remnant population of the Guadalupe fur seal.

On Guadalupe the population of the California sea lion, although larger than previously reported, still was very small, numbering well under 200, and it did not appear to be expanding. The rapidly growing elephant seal population was found to contain more than 4500 individuals. Since there is every indication that the population is still on the steep part of its growth curve, it is predicted that the numbers of this species will continue to increase greatly.

On the San Benitos both California sea lions and elephant seals were extremely abundant (9714 and 908, respectively) and the breeding activities of the elephant seals and the population structure of the sea lions suggested that the populations of both were still expanding.

We examined only the east side of Cedros Island and found no pinnipeds ashore except a herd of 340 California sea lions near North Lighthouse.

Adult male sea lions were conspicuously absent both at sea and on the islands visited. There is some indication that the adult males may move to California after the breeding season.

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The Pacific Floor

Modern methods of undersea exploration have pieced together a dramatic picture of this rugged landscape. A description of it in terms of an imaginary voyage in a supersubmarine

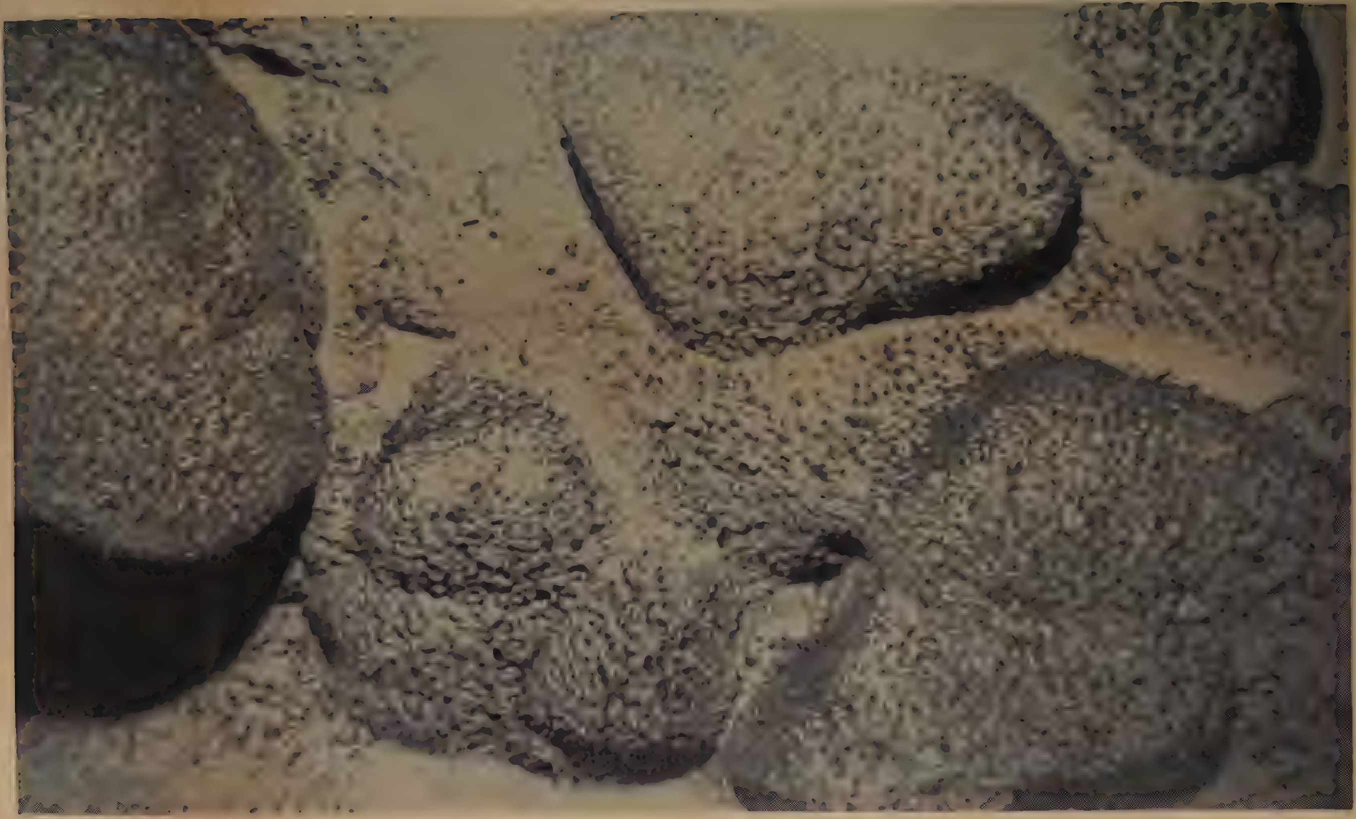
by Robert S. Dietz

THREE great diverse surfaces—interfaces between the different states of matter—cover our planet: the land surface, the sea surface and the interface between sea and land at the bottom of the oceans. With the first two areas we are well acquainted; the interface where land and air meet is man's natural habitat, and he has made himself almost equally at home on the surface of the seven seas. But the third interface, the sea floor, is still a vast unexplored frontier. This immense area, covering 71 per cent of the surface of the globe, has not yet been penetrated by man except at its shallow fringes along the ocean shores. We actually know much less about the topography of the Pacific Ocean floor, for example, than we do about the face of the moon.

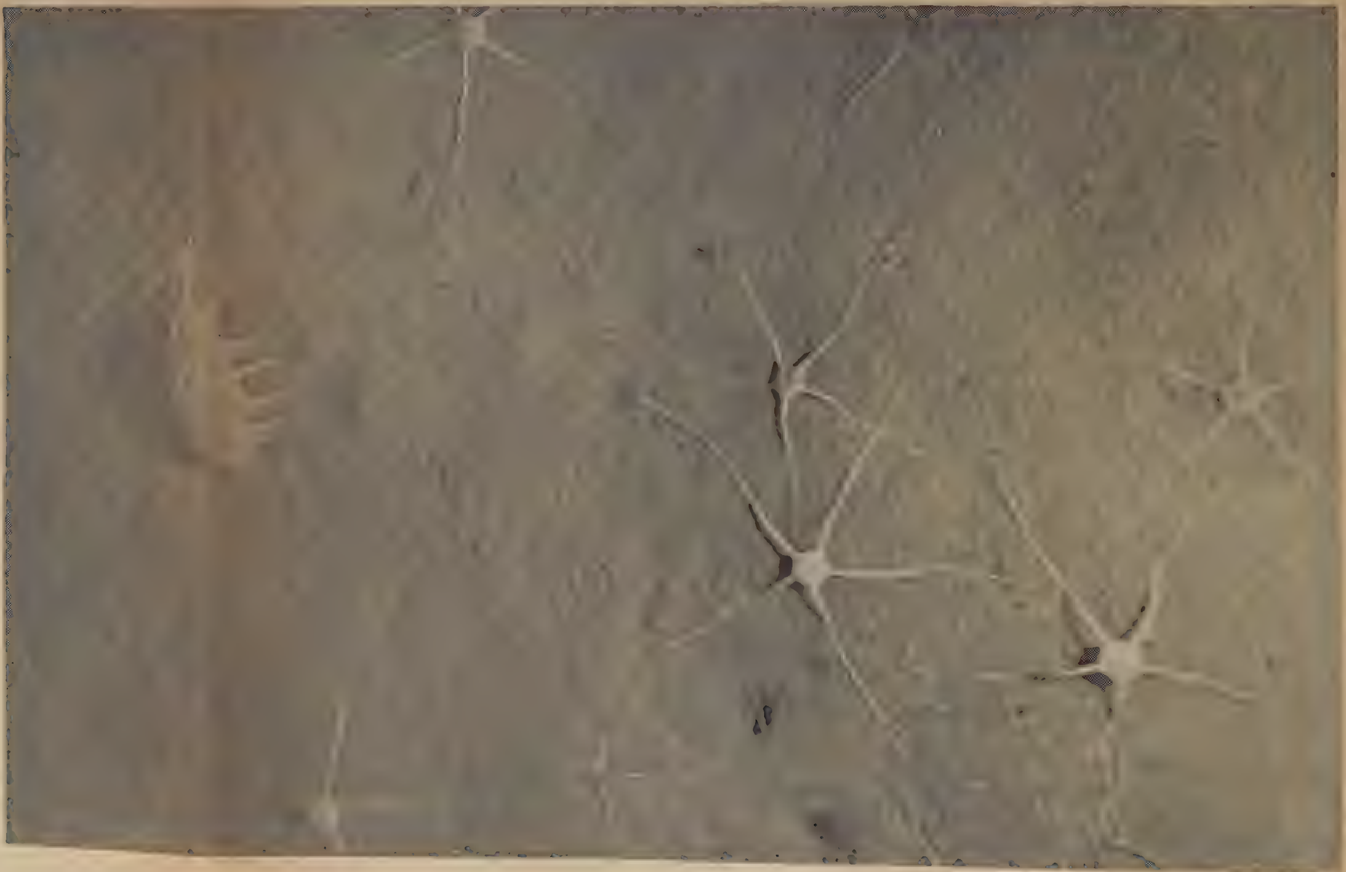
The vast lands beneath the sea must forever remain hidden from any large-scale visual exploration, for even in the clearest water and with the most powerful light we can see no farther than 180 feet. Nor can a "seeing" aid such as radar help us; the oceans are almost opaque to all electromagnetic radiation. But man's inventiveness has at last produced an instrument with which we can begin the exploration of the sea bottom, which has fascinated science and the imagination for centuries. The instrument is sonar: a "searchlight" that uses sound waves. As the atmosphere is the realm of light and other electromagnetic radiation, so the sea is the realm of sound. Sea water is an excellent transmitter of sound waves: a two-pound charge of TNT exploded in deep water off Hawaii can be heard by submerged hydrophones more than 2,300 miles away off the California coast. (If a shot is ever actually "heard 'round the world," it will be fired under water.) Under the sponsorship of the U. S. Navy the science of underwater sound is growing vigorously, and many types of sonar devices have been developed. For the oceanographic explorer the most useful is the echo sounder, which bounces sound pulses off the sea floor.

Thanks to the echo sounder we now have a partial map of the Pacific floor. Let us survey some of these discoveries by taking an imaginary cruise along an explored route on the ocean bottom. We must imagine that we are making the voyage in a submarine for which only Jules Verne, as yet, holds the patent—a true submarine that will carry its own source of oxygen and will have a hull strong enough to stand the great pressure of the deep sea. We must further suppose that we are equipped with advanced sonars of the future which will give us a clear view of the seascape as we proceed on our voyage.

We start from San Diego. Diving to the bottom and heading straight out to sea, we travel for the first 10 miles across a shallow, gently sloping plain—the continental shelf. We have to grope our way slowly here, because the green water is clouded with stirred-up sediment, organic pigments and millions of diatoms, and the teeming marine life produces echoes on our sonar that obscure



ROCKS on the flat top of a mountain 1,500 feet below the surface of the Central Pacific were photographed by means of a special camera. The rocks are coated with a layer of manganese dioxide. Because this substance forms very slowly, it is a measure of the time that has passed since the mountain sank beneath the surface.



CREATURES on the mud bottom of the San Diego Trough 3,600 feet below the surface are a species called the brittle star, and a sea cucumber (*left*). The brittle star bears its name because its arms may easily be broken off. These animals live on the biological refuse that settles out of the waters nearer the surface.

he bottom. The smooth, shallow continental shelf slopes down to only about 330 feet below sea level at its deepest. Extending completely around North and South America, it is believed to have been alternately under and above water as the sea rose and fell in geological time, and its edge is supposed to mark the lowest sea level, *i.e.*, the farthest coastline, of the Ice Age, when the water piled up in glaciers on the land.

TEN MILES OUT the shelf ends abruptly, and we find ourselves at the edge of a scarp, or cliff, that plunges steeply into the deeper ocean. We dive down its face to a depth of more than 1,000 feet, where our sonar view will not be obscured by interfering echoes rom surface organisms or from the deep loating layer of small animal life that shows up on the echo sounder as a phanom bottom ("The Deep-Sea Layer of Life," by Lionel A. Walford; SCIENTIFIC AMERICAN, August, 1951).

The scarp is a convenient feature to ollow as a navigation guide, so we turn iorth and travel along its face. Twenty niles north of San Diego we come to a great gash 1,500 feet deep: the La Jolla Submarine Canyon. Looking remarkably ike some of the famous river canyons n the Sierra Nevadas, this huge steepvalled valley plunges down into the leep undersea trough off San Diego. There it becomes a leveed channel that vinds across the flat bottom of the rough. The levees remind us of the natıral levees built by the Mississippi River n its delta at New Orleans, but these re much larger. They must be produced by mud-charged currents that shoot lown the canyon, flow across the trough, pill over the narrow channel and leave leposits of mud that build up the levees. Perhaps the huge canyon itself has been cut in the continental shelf by such curents through eons of time.

From the submarine canyon we swing vest toward the deeper ocean. On the vay to the abyssal Pacific Basin, we ross a rough badlands of banks and lepressions—a continental borderland vhich is unique to this particular part of he world. Its seascapes are everywhere reen; oozy green muds carpet the bains, and patches of the sandstone known s greensand coat the rocky banks. Its hallower basins are the realm of organsms that live on the rain of organic natter which constantly falls from the urface waters above. The bottoms are opulated by countless millions of serent starfish, in company with mudroveling sea cucumbers and sea spiders. ome of the deeper basins, however, upport little or no life, because their emi-stagnant water lacks oxygen. The rganic matter that rains into them is radually buried and will eventually orm pools of petroleum.

When we turn our special optical searchlight on the banks that rise over the basins, we find them covered with extensive beds of shiny, brown, grotesquely shaped lumps of rock rich in phosphorus. These nodules have grown as crystals grow, by the slow addition of material to their nuclei. In this case they are built up of colloidal particles of tricalcium phosphate from animal shells. In the ancient heart of some of these long-growing nodules we find fossils 15 million years old. On the same banks, scattered among the nodules, are phosphatized whales' ear bones, sharks' teeth and other bones of fish and sea mammals. Someday no doubt these great undersea beds of rock and bone will be mined for their phosphates and rich content of radioactive trace elements.

We cruise on westward for 140 miles across the continental slope and arrive at length at the brink where it drops off to the Pacific Basin itself. Like Pizarro standing on the Andes, we face a breathtaking outlook. Below us falls away a gigantic escarpment as sheer as the east face of the Sierra Nevada and almost twice as high. Here we have reached the real edge of the continent, where the granitic continental rock gives way to the world-girdling foundation of denser basic rock on which the continents float.

THE FLOOR of the Pacific Basin, lying three miles below us, is unlike anything else on earth. It is studded with immense volcanic cones and calderas, vastly larger than any on the continents, and is split by huge fault blocks and scarps. Along the base of the continental cliff stand several great sea mountains. But most striking is the fresh, youthful look of the topography. It looks as if it was created only yesterday. The volcanic cones have the classically simple forms of textbook diagrams of volcanoes, and the fault scarps rise like the straight sheer faces of blocks several thousand feet high. This pristine simplicity is not, however, a sign of youth; it is the result of excellent preservation, due to the protection of the seascape from weathering. Unlike mountains on the land, the seamounts have been free from the erosion of wind, rain, streams or ice. Largely untouched by erosive forces, they are physiographic museum pieces still standing as they were when formed eons ago.

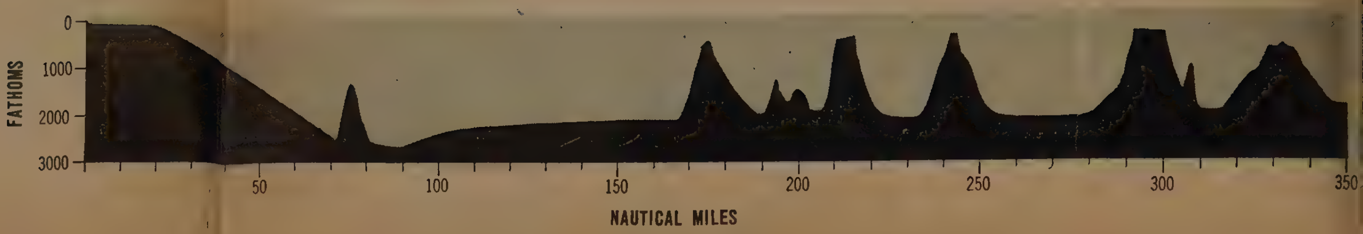
Before we go on with the journey, let us take a little time to inspect the sea floor closely. In the hollows and basins between the mountains and knolls are ponded deposits of a soft, fine-grained red clay such as has never been seen on the continents. Its red color indicates an oxidized state, which in turn shows that very little organic matter is deposited here. For one thing, the surface waters of the deep Pacific are relatively poor in nutrients, so they grow only about one per cent as much organic matter as the richer waters inshore. For another, the solvent power of the cold water masses, rich in carbon dioxide, that flow in from the Antarctic prevents permanent deposition of any of the organic material that may fall here from the surface.

We now turn our submarine to follow the steep continental escarpment northward. Cruising at 2,400 feet below sea level to avoid bucking the strong southsetting California Current near the surface, we explore the rugged face of the great scarp, broken by deep gullies, landslides and enormous mudflows. Off Monterey Bay, California, we pass one of the great submarine canyons of the world. Fifty miles long and more than 7,000 feet deep, it compares in grandeur with the Grand Canyon. Farther north, off Cape Mendocino, we run into a two-mile-high escarpment that branches from the main north-south scarp and heads out almost at right angles toward the west. We could follow this winding cliff for 1,000 miles and still not find the end of it. It evidently marks a major boundary in the earth's crust, because to the north of it the sea floor is about a half-mile higher, indicating that its rock is lighter—intermediate in density between the continental and the oceanic rock types.

Soon we are cruising along the floor of the Gulf of Alaska, a smooth plain that slopes toward the southwest. The floor is covered with a gray, felt-textured ooze composed of the shells of countless millions of diatoms that have settled down from the surface waters. Here and there seamounts projecting through this sea of ooze rise up 5,000 to 8,000 feet, to within a mile or less of the sea surface. Most of them have broad flat tops.

THESE table mounts, called guyots, look like decapitated volcanoes, and that is exactly what they are. Their tops must have been cut off by some knife-edged erosive process. In the realm of the sea there is only one way that such a clean job of decapitation could have been accomplished: by the action of surf. In other words, their tops once stood above the water as islands and were sliced off by breakers cutting into them. This conclusion is confirmed by the fact that their flat tops are fringed by a narrow border of rounded cobblestones—the remains of their ancient cobble beaches.

These ancient islands are now deeply drowned below the surface of the sea. What caused them to fall so far below the sea level? Our echo sounder provides a clue. Several of the table mounts are surrounded by depressions, or moats, around their bases; they look like a coffee cup turned upside down in a saucer. It is tempting to conclude that they sank because the mountain mass bent down



CROSS SECTION of a part of the Gulf of Alaska shows the continental shelf (*left*), the Aleutian Trench (*at the bottom of the shelf*) and a chain of nine seamounts. The tallest of the mounts rises 11,214 feet from the bottom of the Gulf. The top of the mount that stands in the Trench is 7,000 feet below the surface.

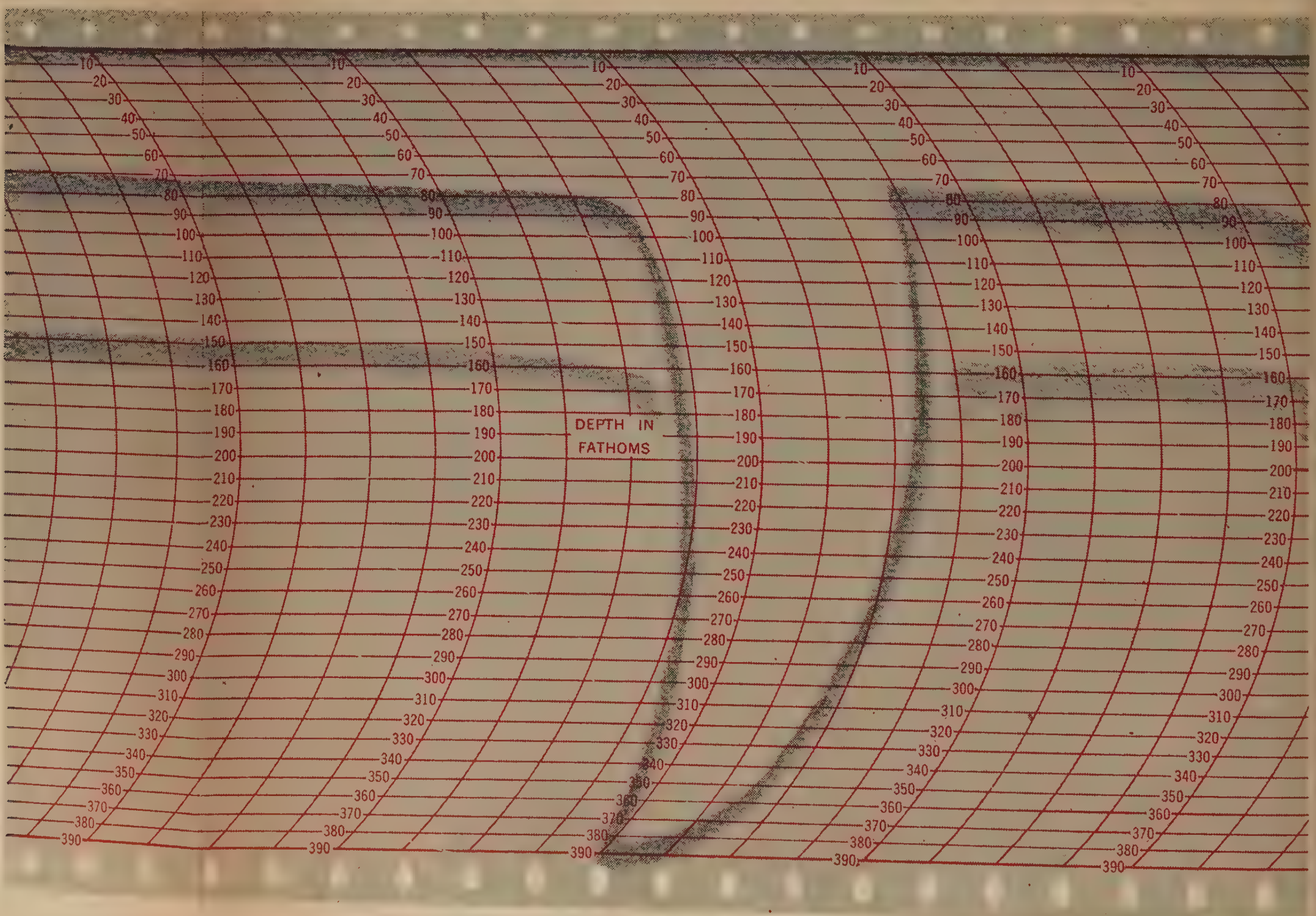
the earth's crust, much as a small boy standing on thin ice bends down the ice over a large saucer-shaped area.

But movement and buckling of the crust itself has also contributed to the drowning of some of the guyots. As we drive north into the great undersea valley known as the Aleutian Trench, we can see evidences of this. On the south flank of the Trench is a table mount whose top is tilted in toward the Trench; evidently it was first decapitated and then tilted over when the Trench was formed by downbuckling of the crust. There is another guyot standing on the bottom of the Trench, and its flat top is 7,000 feet below the sea surface—the most deeply drowned guyot we have seen. In all likelihood the formation of the trough is responsible for its deep sinking. Geological evidence indicates that the Trench is at least 15 million years old, so the two guyots must be older than this. The sea mountains truly are long-lived; on land a similar mountain would be worn away by erosion in a few million years at most.

Strewn over the tops of some guyots we find occasional boulders of granite and other continental rocks. This is a startling discovery: How did they get out here in the deep ocean? Probably, a little reflection suggests, they were ferried out from the continent by icebergs of the Ice Age and dropped on the guyots when the ice melted.

FROM THE Aleutian Trench we turn south and, steering by our gyrocompass, head for the Hawaiian Islands. The islands themselves are only the occasional surface projections of a great 1,800-mile volcanic ridge that stretches almost continuously from the island of Hawaii to Midway Atoll. The ridge lies along the axis of a broad low swell of the sea floor dotted with numerous sea knolls and seamounts: the foothills of the mountain range. Here and there long straight fault scarps strike across the swell. Along the base of much of the ridge are deep moats and terraces, showing that the islands are sinking and the crust is being depressed by the great mass of the ridge. The subsidence is greatest toward the northwest end of the island chain.

This sinking would long ago have drowned the atolls were it not for the fact that they are constantly being built



FATHOGRAM, the record of an echo sounder, shows the cross section of Astoria Canyon at the mouth of the Columbia River. The sides of the canyon are curved by the convention of the record. The horizontal line at about 80 fathoms is the continental shelf; the second line at about 160 fathoms, the bottom of the shelf.

p by the skeletal remains of corals and
oralline algae. These animals and
lants, which thrive in the warm waters,
aintain a coral reef at the sea surface
the foundation slowly subsides.

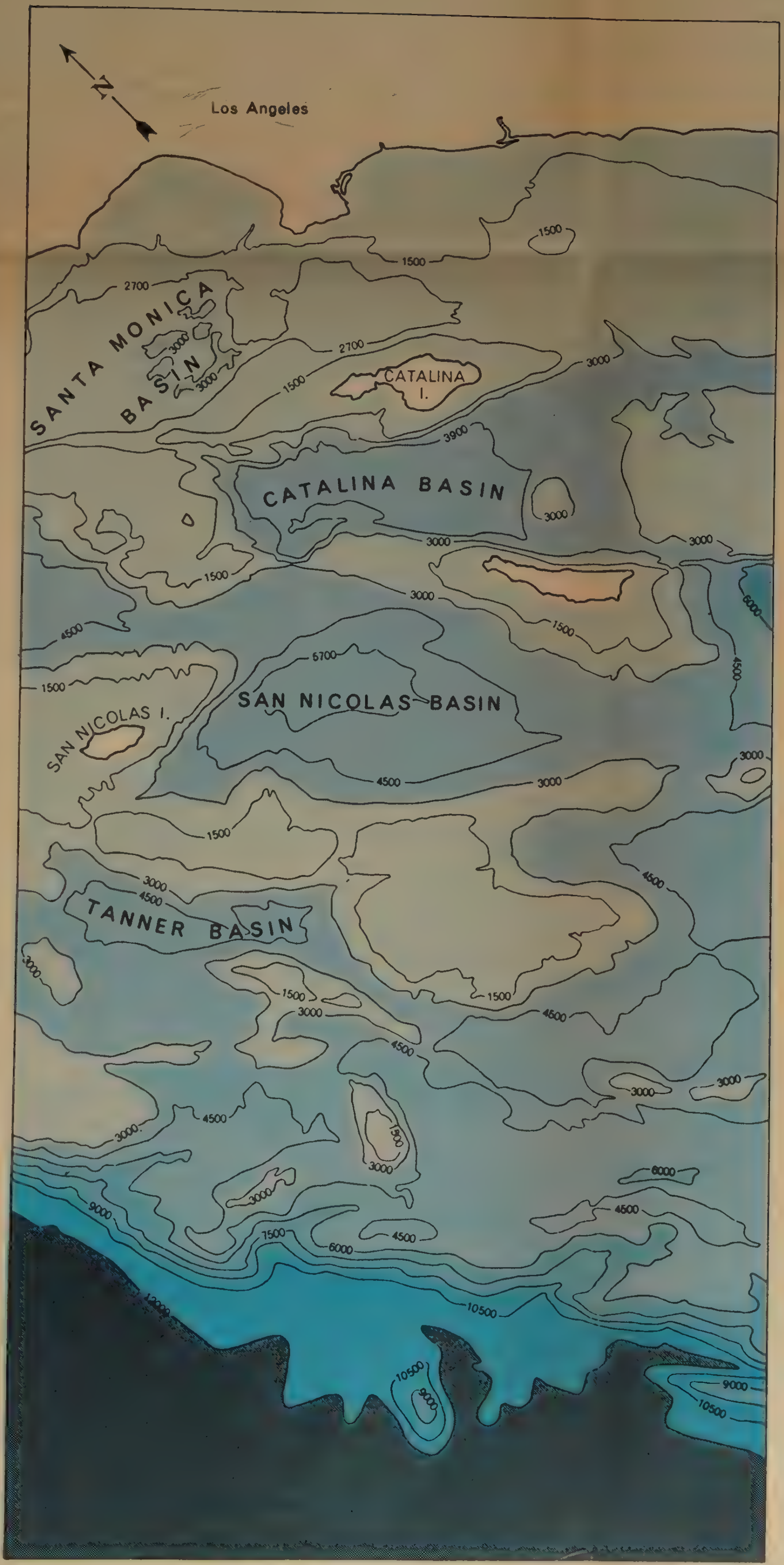
From the Hawaiian Islands we cruise
est 300 miles to the Mid-Pacific Moun-
ins. This mountain range lies com-
etely submerged in the region between
e Hawaiian Islands and Wake Atoll.
rom the top of the mountain mass rise
number of tall guyots, as the volcanoes
ount Hood and Mount Rainier project
ove the Cascade Mountains of the
ockies. Some of the guyots have daz-
ng white caps, like mountains on land,
it the caps, of course, are not snow.
ey consist of a white ooze made of
e remains of certain small protozoa
members of a family of floating foram-
fera) which have shells of calcium
rbonate. These animals live in profu-
n in the waters of the tropical Pacific,
d their dead shells form extensive de-
sits in the shoaler parts of the Pacific.

Coral reefs fringe the tops of some of
e mile-deep guyots, but these deeply
owned formations are dead: corals do
t grow at depths below about 180 feet.
e dead animals composing these reefs
e ancient, extinct types, some of them
out 100 million years old. These fos-
give us positive proof that the guyots
indeed truncated ancient islands of
Pacific. We can only speculate as to
y the building of these reefs failed to
p pace with the sinking of the guy-
, as it did elsewhere. A period of cold
y have killed off the corals, or the
ots may have sunk too rapidly for
reproduction of the animals to main-
n the atoll at sea level.

The evidence of the coral fossils shows
t the Pacific Ocean must have been
east two miles deep 100 million years
, when the coral was growing on
se guyot tops, because the sinking
ots still stand two miles above the
ounding Pacific sea floor.

omanticists may be tempted to im-
ne that these guyots were once peo-
l by a race of human beings who
e wiped out by a catastrophic rise
ne sea—a kind of Pacific counterpart
ne lost continent of Atlantis. But man
not arrive on the earth until a mil-
years ago at the earliest, and the
ots had disappeared into the ocean
before that. It is possible, however,
geological history will repeat itself:
the Hawaiian Islands, a present-day
nterpart of the Mid-Pacific Moun-
, will eventually be cut to shallow
s and, like them, slowly sink be-
h the sea.

Robert S. Dietz is an oceanographer at the U. S. Naval Electronics Laboratory in San Diego, Calif.



SUBMARINE TOPOGRAPHY off the coast of Southern California consists of a rugged system of swells and depressions. The contour intervals are given in feet. This map was prepared by the American Geographical Society.

THE BALL-BREAKER, A DEEP WATER BOTTOM SIGNALLING DEVICE[1]

By

JOHN D. ISAACS AND
A. E. MAXWELL

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ABSTRACT

A simple device for signalling the arrival of a deep cast on bottom has been developed and is now in routine use. The device is used either in line with corers or is suspended below as a pilot. When contact of either the ball-breaker or other apparatus is made with the bottom, a small glass sphere in the former is imploded and the resultant signal at the surface is amplified and reproduced over a loud speaker system. The device has been used successfully at depths to 2,700 fathoms.

General. With the present-day trend toward deep water oceanography, many difficulties have arisen which were not encountered in shallow water operations. Among these difficulties is the problem of determining the exact time when a piece of oceanographic equipment reaches bottom. This is not serious in shallow water, since sensitive dynamometers have been constructed which indicate to the observer aboard ship the moment that the tension on the cable is relieved. However, in deep water the weight of the equipment is often only a small fraction of the total weight of cable and of variable loads imposed by the ship's roll; therefore, no conclusive effect upon tension can be observed when the apparatus encounters bottom.

Obviously, the answer to this problem may be found by employing some device which is independent of both the ratio of equipment to cable weight and the depth of the water. To meet this need, an instrument was developed which imploded a small glass sphere when the apparatus hit bottom. The resulting implosion, picked up at the surface by a simple hydrophone, is amplified and reproduced audibly over a loudspeaker system.

Development. The original method used to trip the mechanism and to break the glass sphere is shown schematically in Fig. 1. The apparatus is very simple; it merely employs a piston fitted with a sharp point which is allowed to fall when the equipment contacts the bot-

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[1] Contribution from The Scripps Institution of Oceanography, New Series, No. 565. This work represents results of research carried out for the Office of Naval Research and the Bureau of Ships under contracts with the University of California.

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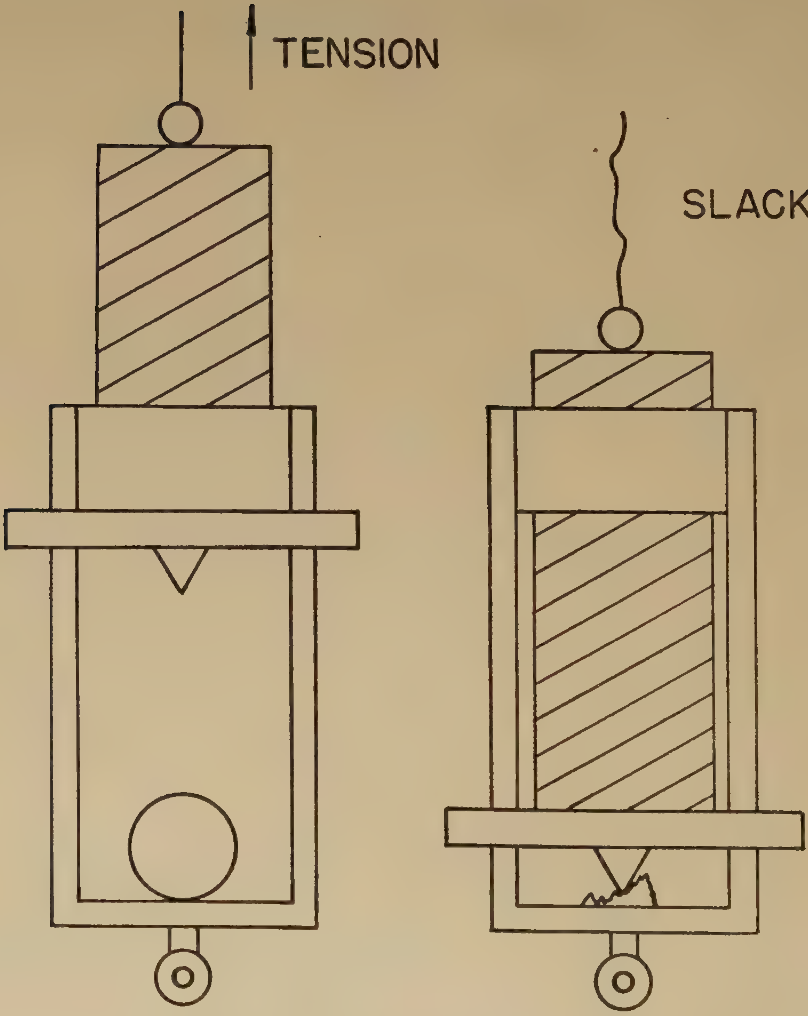


Figure 1. Schematic of early model ball-breaker showing method of tripping.

tom, thus imploding the glass sphere. Such a straight-forward device would seemingly present no problem in its initial design; however, as is often the case in oceanographic operations, equipment which appears to be encouraging on the drawing board and which works well in test tanks may fail entirely when lowered into the ocean. Such was the case with the early models of this device.

The first model functioned satisfactorily in shallow water, but in deep water the point succeeded only in chipping the glass ball and was therefore ineffective. It was thought that the cable stretched elastically under the loads and then contracted as the equipment reached bottom, thus allowing the piston to lower gently upon the glass sphere. This problem was solved by incorporating a tripping mechanism in the device to allow the piston to drop freely on contact with bottom.

However, with this new model a great many failures in breaking the ball were experienced, since some balls were entirely fractured but were held together by the pressure; thus they failed to implode. It became apparent that the glass balls acquired great strength under compression in much the same manner as an arch can carry greater concentrated loads under a large dead load than it can with a small dead load. To eliminate this difficulty, the chisel point tip was replaced with a conical tip in the hope of reducing the area of impact upon the sphere, but then the conical tip and the glass wedged together in a pressure tight seal as though the glass were plastic; again implosion was prevented. To avoid sealing, the tip was relieved in three places so that shearing and bending might occur in the glass to facilitate collapse. This proved successful in all subsequent trials.

Description and Techniques. Fig. 2 shows the instrument in its present form. The glass sphere is centered by three tips and is held into place by a turn of friction tape. A more complex holding device does not appear to be practical since projections are blown off by the implosion. Located inside the cylinder is the tripping mechanism which releases the piston upon contact of the device with the bottom. The ring on the bottom provides a means of securing other instruments below the ball-breaker if it is to be used as an in-line device.

There are several types of glass spheres which are available commercially and which appear to be satisfactory. Preliminary pressure tests of various samples have shown that some of these balls are capable of withstanding pressures up to 16,000 psi. The balls, made commercially for ornamental purposes from ordinary glass, are approximately two and one-half to three inches in diameter and have an average wall thickness of 1/16 inch. The glass may contain a large number of air bubbles and may often be irregular as to size and shape; but these minor irregularities do not appreciably effect the efficiency of the balls. However, care must be taken to eliminate those balls that have a small hole at the point where they are sealed, since water in the balls render them ineffective. The balls are tested by securing several balls in a cloth sack and by lowering them a few hundred meters in the water. Experience has shown that the balls should be separated

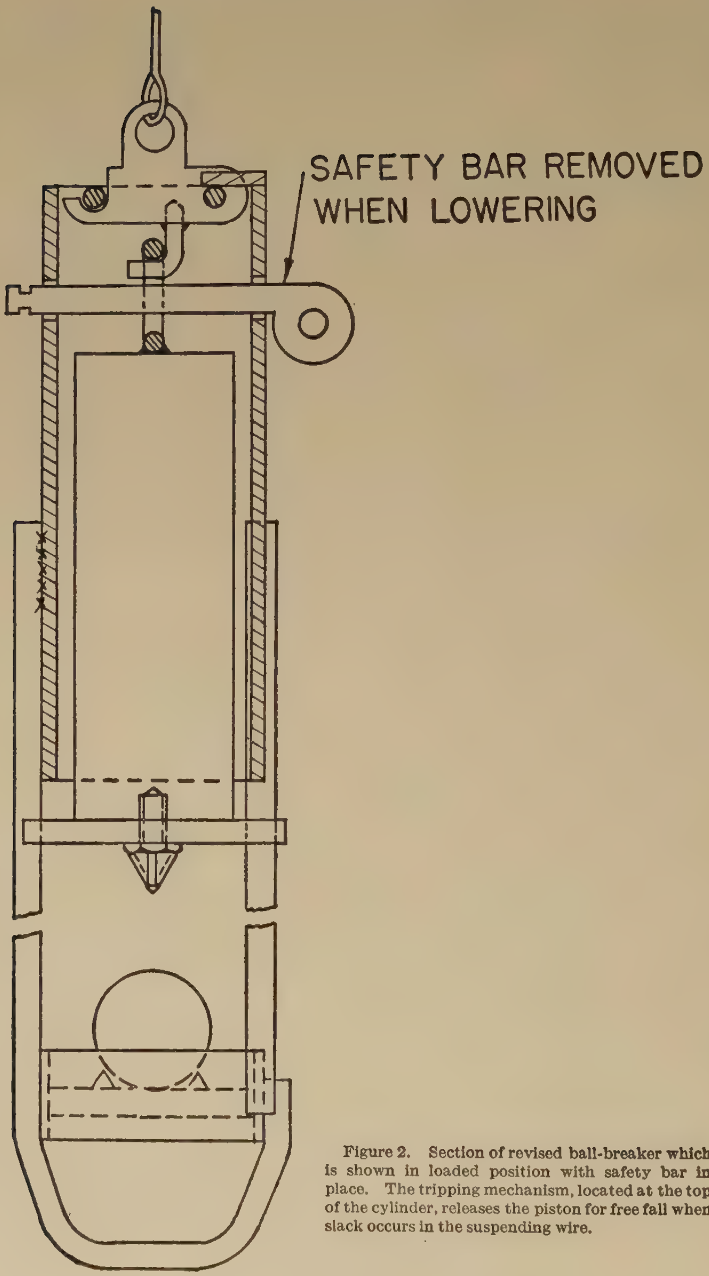
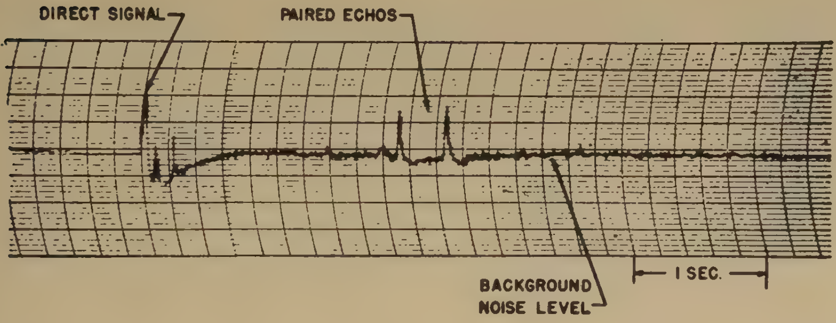

SAFETY BAR REMOVED
WHEN LOWERING

Figure 2. Section of revised ball-breaker which is shown in loaded position with safety bar in place. The tripping mechanism, located at the top of the cylinder, releases the piston for free fall when slack occurs in the suspending wire.

into two classes: thick spheres with about ⅛-inch walls for use in depths greater than 3,000 fathoms, and thinner spheres with walls approximately $\frac{1}{16}$-inch thick for use in water less than this depth. In this way the balls are segregated into divisions which give maximum efficiency by avoiding premature failures.

IMPLOSION OF LIGHT BULB BETWEEN SURFACE AND BOTTOM. DEPTH OF WATER 1000 FATHOMS.



IMPLOSION OF GLASS SPHERE ON BOTTOM AT A DEPTH OF 1000 FATHOMS

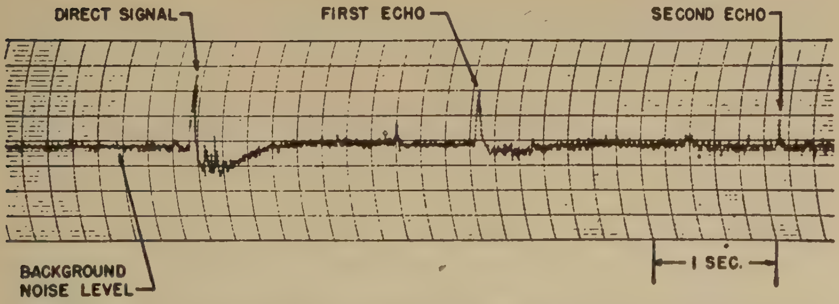


Figure 3. Traces of two implosions illustrating the different types of echoes encountered.

Surprisingly, it is found that the peak intensity of the signal received from these implosions is practically independent of the depth of implosion; that is, the increase in attenuation is offset by the increase in *peak* energy obtained at greater depths. Such appears to be the case for signals which have originated at depths from 200 to 2,700 fathoms, although no quantitative measurements have been made. Although it might be expected that an increase in the diameter of the sphere would result in a corresponding increase in the peak signal intensity, preliminary tests show that this is not the case. Possibly the larger air mass, corresponding to the larger volume, produces a cushioning effect which tends to reduce the peak energy released.

At the surface, the signal is picked up by a simple magnetostriction-type hydrophone which is lowered over the side about one hundred feet below the surface to reduce the background noise. The signal and echoes are very sharp and are easily distinguishable from the background noise, the signal above background noise being of the order of 20 d.b. The echoes act as a verification of the implosion, and further, the spacing of the echoes permits the determination of the relative depth of the implosion. If the ball breaks prematurely before hitting bottom, paired echoes are heard, while only single equally-spaced echoes are heard when the ball is broken on the bottom. The two traces in Fig. 3 were taken from a tape recording made of actual implosions at sea. Both implosions took place at the same ship's position. The upper graph is a recording of the sound from a common 25-watt light bulb which imploded under pressure at a depth of about 4,500 feet. The graph shows that the peak signal intensity is much higher than the background noise and, as would be expected, paired echoes are heard. In the lower graph a glass sphere is imploded on bottom by means of the ball-breaker device, and the resulting signal and two echoes are clearly discernible. These echoes are single and evenly spaced, thus verifying that the instrument reached bottom. Four echoes have been heard in depths of 2,500 fathoms, the number depending primarily upon the amount of background noise present and the state of the sea.

Remarks. This apparatus has been highly successful in deep-water operations where small cores have been taken, and it should be practical for a wide range of oceanographic operations. It should also be mentioned that a spring-loaded model has been designed which sacrifices the simplicity of the existing model for a reduction in total weight.

Acknowledgments. The authors are indebted to the Northwest Glass Company of Seattle, Washington and to the Blenko Glass Company of Milton, West Virginia for their cooperation and for the supply of glass balls used for the original development.

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FUR SEALS PREYING ON BLACK-FOOTED ALBATROSS[1]

It has been stated (Miller, Condor, **42**: 229–238, 1940; Yocum, Auk, **64**: 507–523, 1947) that the Black-footed Albatross (*Diomedea nigripes*) is almost completely free from predators while at sea. Nevertheless, mammals other than man have been observed to attack these birds. On the night of April 5, 1949, the author was fishing with the aid of a light from the deck of the Scripps Institution vessel "Horizon." Two Black-footed Albatrosses were riding the surface at the outer edge of the lighted area, picking up the fishes that came their way. A seal was also feeding on these fishes (*Cololabis saira, Myctophum affine, Tarletonbeania crenularis*) beneath the surface. Twice it rushed at the legs of the birds, and finally drove them away. The next morning a seaman on watch reported having seen a seal pull an albatross under, and the bird did not reappear.

These observations were made at approximately 35° 44′ N. Lat., 128° 37′ W. Long. Since this position is about 300 miles from the nearest point of land, it is almost certain that the predator was the Pribilof fur seal (*Callorhinus ursinus*). Clemens, Hart, and Wilby (Analysis of stomach contents of fur seals taken off the west coast of Vancouver Island in April and May, 1935. Dept. Fisheries, Ottawa, Canada, 1936) have reported a Marbled Murrelet (*Brachyramphus marmoratum*) in a fur-seal stomach.—J. L. McHUGH, *Virginia Fisheries Laboratory, Gloucester Point, Va.*

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MENDOCINO SUBMARINE ESCARPMENT

HENRY W. MENARD AND ROBERT S. DIETZ

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MENDOCINO SUBMARINE ESCARPMENT[1]

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ABSTRACT

A submarine scarp extends westward from Cape Mendocino, California, for at least 1,200 miles. Its height at 70 miles from shore is about 10,500 feet, and 1,000 miles from shore it is about 8,420 feet. The maximum average slope from top to bottom ranges from 7° to 10°; but portions of the scarp 1,000 feet high have slopes as great as 18°–24°. The scarp lies on the south side of a ridge which has a gentler slope toward the north in most places. Similar, but smaller, ridges and scarps are found to the north and south of the Mendocino Scarp and are parallel to it. Regional bathymetry shows that the sea floor for hundreds of miles south of the scarp is about $\frac{1}{2}$ mile deeper than the sea floor for hundreds of miles north.

The scarp does not appear to be a seismically active submarine extension of the San Andreas fault, which passes out to sea at Cape Mendocino. Epicenters of submarine earthquakes trend northwest from Cape Mendocino rather than west along the Mendocino Scarp. The origin of the scarp is uncertain, but three hypotheses are considered. These suggest that it may be (1) a submerged "continental slope" between "continental" rocks to the north and oceanic rocks to the south, (2) a reverse fault, or (3) a strike-slip fault.

INTRODUCTION

THE "HORIZON" SURVEYS

At the suggestion of the writers, the homeward course of the Scripps vessel "Horizon" from Bikini Atoll to San Diego, California, was directed north of the shortest route in order to determine whether a great submarine scarp extends far to the west from Cape Mendocino, California. The reconnaissance of the scarp was the concluding part of the joint Scripps Institution of Oceanography and Navy Electronics Laboratory Expedition to the Mid-Pacific, 1950. The previously questionable existence of the scarp was verified by detailed sounding lines at four crossings with a spacing of 100–200 miles.

In August, 1951, the "Horizon" made a more detailed reconnaissance of the scarp as a part of "Operation Northern Holiday." Eighteen crossings of the scarp had an average spacing of about 50 miles, and a course was run along the scarp for about 100 miles in a search for submarine canyons.

In the present paper the topography along the Mendocino Scarp is described on the basis of the "Horizon" surveys and earlier soundings from all sources; a tectonic interpretation of the topography is also included.

PREVIOUS KNOWLEDGE

The first account of a part of the submarine topography off Cape Mendocino (Murray, 1939) was based on United States Coast and Geodetic Survey soundings and included a chart, with a contour interval of 100 fathoms, showing the bathymetry of the sea floor for a distance of about 70 miles from the shore. Shepard and Emery (1941) also used Coast and Geodetic Survey soundings to prepare a chart of about the same area with a contour interval of 50 fathoms. They noted, moreover, that "sporadic" soundings suggested that the scarp could be traced at least 400 miles west of the coast. More recently Colbert (1949) and Studds (1950) have referred briefly to the scarp in annual summaries of the results of Coast and Geodetic

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[1] This paper is a joint contribution of the United States Navy Electronics Laboratory and the Scripps Institution of Oceanography. Contributions from the Scripps Institution of Oceanography, new series, no. 567. Manuscript received July 23, 1951.

Survey work; new crossings of the inshore part of the scarp were made by Survey ships traveling to and from the Aleutian Islands. Colbert stated that ". . . an indication was obtained of a continuation of the submarine scarp off Cape Mendocino, California, to a point 300 miles seaward." Studds said: "The westward continuity of the submarine scarp off Cape Mendocino, California, was substantiated at a distance of 200 miles off the coast."

The Mendocino and Gorda scarps (Shepard and Emery, 1941) are unusual topographic features because of their combined great length, because they trend perpendicular to the "concordant" coast of the Pacific Ocean, and because few scarps of any kind are known to exist on the floors of the deep oceans. It is interesting to note, however, that a long submarine scarp trending perpendicular to the shore was discovered by Dietz (1952) on the United States Navy Antarctic Expedition of 1946–1947. This scarp extends along longitude 35° E. for at least 300 miles from Antarctica. It has an average slope of 44° and a height of 9,600 feet; the top is at 1,100 fathoms and the bottom at 2,700 fathoms. The Antarctic scarp also resembles the Mendocino and Gorda scarps, in that it lies on the steep side of an asymmetrical ridge.

NAME OF THE SCARP

No official name has been assigned to the great submarine scarp which is the subject of this paper. However, some name, even though unofficial, is required in order to avoid awkwardness and ambiguity. The choice of a name is complicated by matters which will now be outlined.

Shepard and Emery (1941) applied the name "Gorda Scarp" to the north-facing scarp, which extends 70 miles from shore (to the edge of their chart). The name was selected because the closest approach of the scarp to the shore is off Punta Gorda, a comparatively minor promontory 13 miles south of Cape Mendocino. At about 30 miles beyond the area shown in Shepard and Emery's chart the north-facing scarp becomes more subdued, but the westward topographic trend continues along a much higher south-facing scarp, which lies about 15 miles to the south. The south-facing scarp extends for at least 1,100 miles. This long south-facing scarp has not been named, unless it is considered to be an extension of the Gorda Scarp. The writers consider the two scarps to be separate, although they have the same trend and probably are parts of a "Mendocino trend" or "Mendocino structure." The south-facing scarp hereinafter is called the "Mendocino Scarp" because of its close relation to Cape Mendocino. At Cape Mendocino the regional trend of the coast changes from northwest to north, and the cape is a major promontory. As such, it is named on most charts and maps which show this area, even small-scale charts of the world. It seems suitable to name a great submarine scarp after a prominent geographical feature which is easy to locate.

The name "Mendocino Escarpment" or "Scarp" has also been applied to the near-shore, north-facing scarp which Shepard and Emery (1941) call the "Gorda Scarp." The first published mention of the scarp (Murray, 1939) refers to it as a "submarine scarp off Mendocino, California," without assigning a name. Smith (1941) called it the "Mendocino Escarpment," but in subsequent statements representatives of the Coast and Geodetic Survey have returned to "submarine scarp off Cape Mendocino" (Colbert, 1949; Studds, 1950). The present writers, however, prefer to use "Gorda Scarp" for the inshore north-facing scarp, in order to differentiate it from the larger south-facing scarp.

SOURCES OF SOUNDINGS

Soundings used in constructing a bathymetric chart of the Mendocino Scarp are located on figure 1. Most soundings within 250 nautical miles of the coast were made by the "Horizon" and by ships of the U.S. Coast and Geodetic Survey. The contours within 70 miles of the shore are taken in part from Shepard and Emery (1941). The research ship "Carnegie" took one line of soundings about 250 miles from shore. Beyond 250 miles from the coast, the chief sources of soundings are the surveys by the "Horizon," and spot soundings by U.S. Navy ships, principally the "U.S.S. Ramapo." The "U.S.S. Burton Island" helped to correct a preliminary interpretation of the topography by making spot soundings in several critical unsounded areas. The 22-fathom sounding at 46°–45° N., 130°–147° W., was made during a survey by the U.S. Fish and Wildlife Service ship, "John Cobb."

CORRECTIONS IN SOUNDINGS

Most echo sounders are calibrated by assuming a sound velocity of 4,800 feet per second. However, the velocity of sound in the sea varies with temperature, salinity, and pressure, so that the assumed velocity is rarely correct, although the percentage error from this cause is small. For example, the "Carnegie" determinations of sound velocity (Fleming *et al.*, 1945) indicate that a correction of only 60 fathoms should be added to a sounding of 2,500 fathoms in the vicinity of the Mendocino Scarp. Hydrographic Office charts show uncorrected soundings because they are more useful than corrected ones for navigation. The contours figured in the present paper are based on uncorrected soundings.

Errors due to inaccurate positions, defective instruments, and faulty readings are more significant in the preparation of bathymetric charts than are errors due to uncorrected sound velocities. A rational bathymetric chart rarely can be drawn if all soundings are accepted as correct. A line of soundings which disagrees with other lines which it crosses may justifiably be rejected. Some sounding lines, clearly erroneous, were rejected in preparing the bathymetric charts; the positions of the rejected lines are shown in figure 1.

The writers have applied corrections for the variation of sound velocity with depth in computing the height and slope of the scarp from the "Horizon" soundings. Heights derived from corrected depths are expressed in feet in the text, and heights from uncorrected depths are expressed in nautical miles or in hundreds of feet. All distances are in nautical miles.

DESCRIPTION OF BATHYMETRY

REGIONAL BATHYMETRY OF THE NORTHEASTERN PACIFIC OCEAN

The submarine topography of the abyssal sea floor off the west coast of North America (fig. 2) may be separated into three distinct provinces. From Alaska south to about latitude 40° N., the sea floor is a rather smooth plain, sloping from the continent toward the west. A number of submarine volcanoes rise above the plain in the Gulf of Alaska. Many northeast-trending ridges and troughs have been found off Oregon and Washington. Far to the south, off

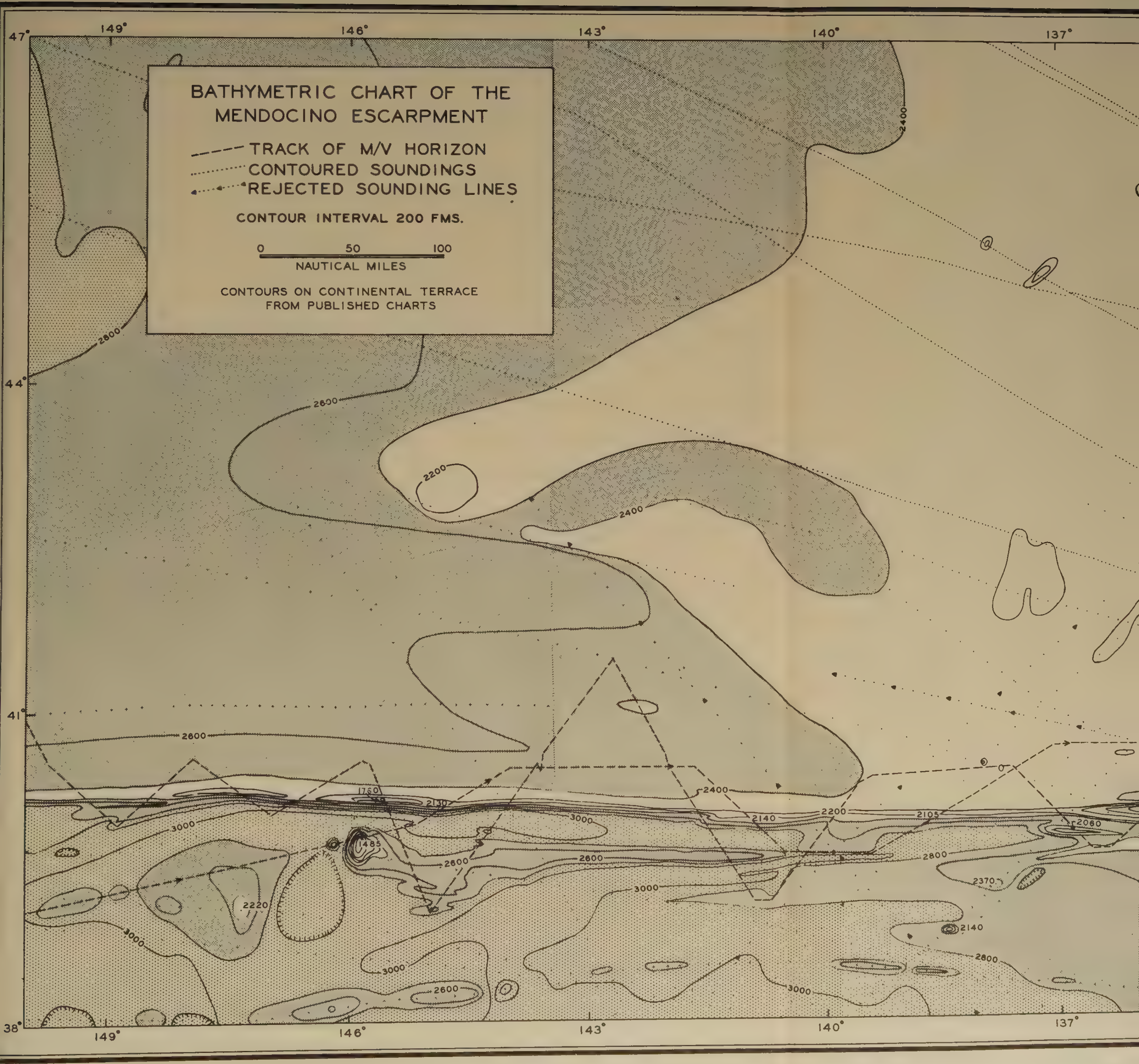
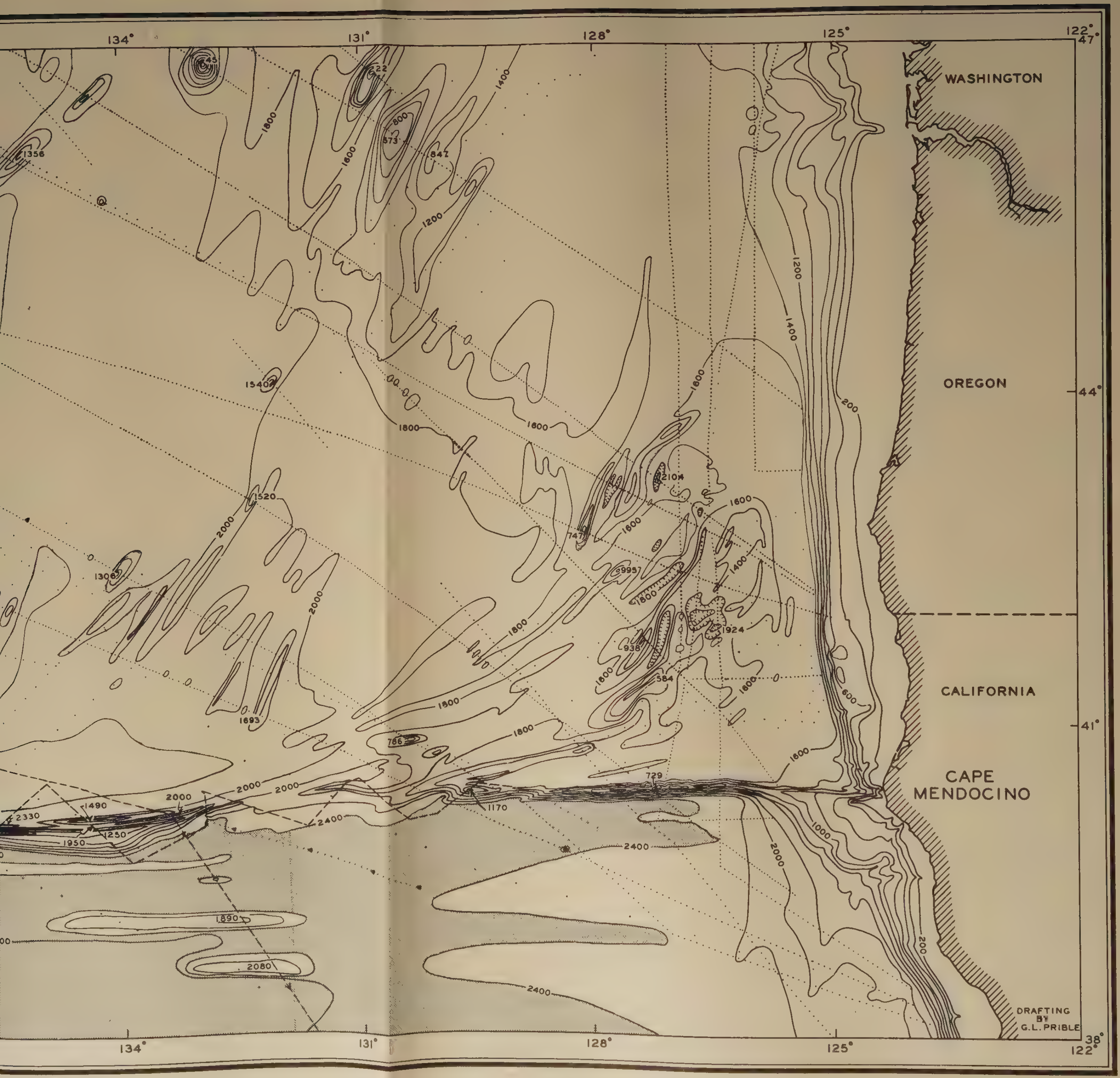

BATHYMETRIC CHART OF THE MENDOCINO ESCARPMENT
TRACK OF M/V HORIZON
CONTOURED SOUNDINGS
REJECTED SOUNDING LINES
CONTOUR INTERVAL 200 FMS.
0
50
100
NAUTICAL MILES
CONTOURS ON CONTINENTAL TERRACE FROM PUBLISHED CHARTS
47°
149°
146°
143°
140°
137°
44°
41°
38°
2400
2800
2600
2200
2400
2600
2400
1760
2130
2200
2140
2105
2060
3000
3000
1485
2600
2600
2800
2370
3000
2220
2140
3000
3000
2600
2800
3000

FIG. 1.—Bathymetric chart of the Mendoci


134°
131°
128°
125°
122°
47°
44°
41°
38°
WASHINGTON
OREGON
CALIFORNIA
CAPE MENDOCINO
645
722
1356
800
573
847
1200
1400
1800
1600
1540
1520
2000
1308
1693
2104
747
995
938
1924
584
200
600
1000
786
729
1170
1490
2330
1250
1950
2400
1890
2080
DRAFTING BY G.L. PRIBLE

scarpment. Contour interval 200 fathoms

Baja California, Mexico, is a mountainous rise, at a depth of about 2,200 fathoms, which is studded with submarine volcanoes. The rise is separated from the continent by a deep elongate trench parallel to the coast. Off central and southern California, between the "Alaskan plain" and the "Mexican rise," the sea floor is depressed about ½ mile, so that it is as deep as much of the central part of the Pacific Ocean. A long asymmetrical ridge—trending approximately perpendicular to the coast—lies between the "Alaskan plain" and the deep area off California. The ridge has a higher and steeper slope toward the deep to the south and a less steep slope toward the shallower floor to the north. The south side of the ridge is the Mendocino Scarp. The scarp is considered to

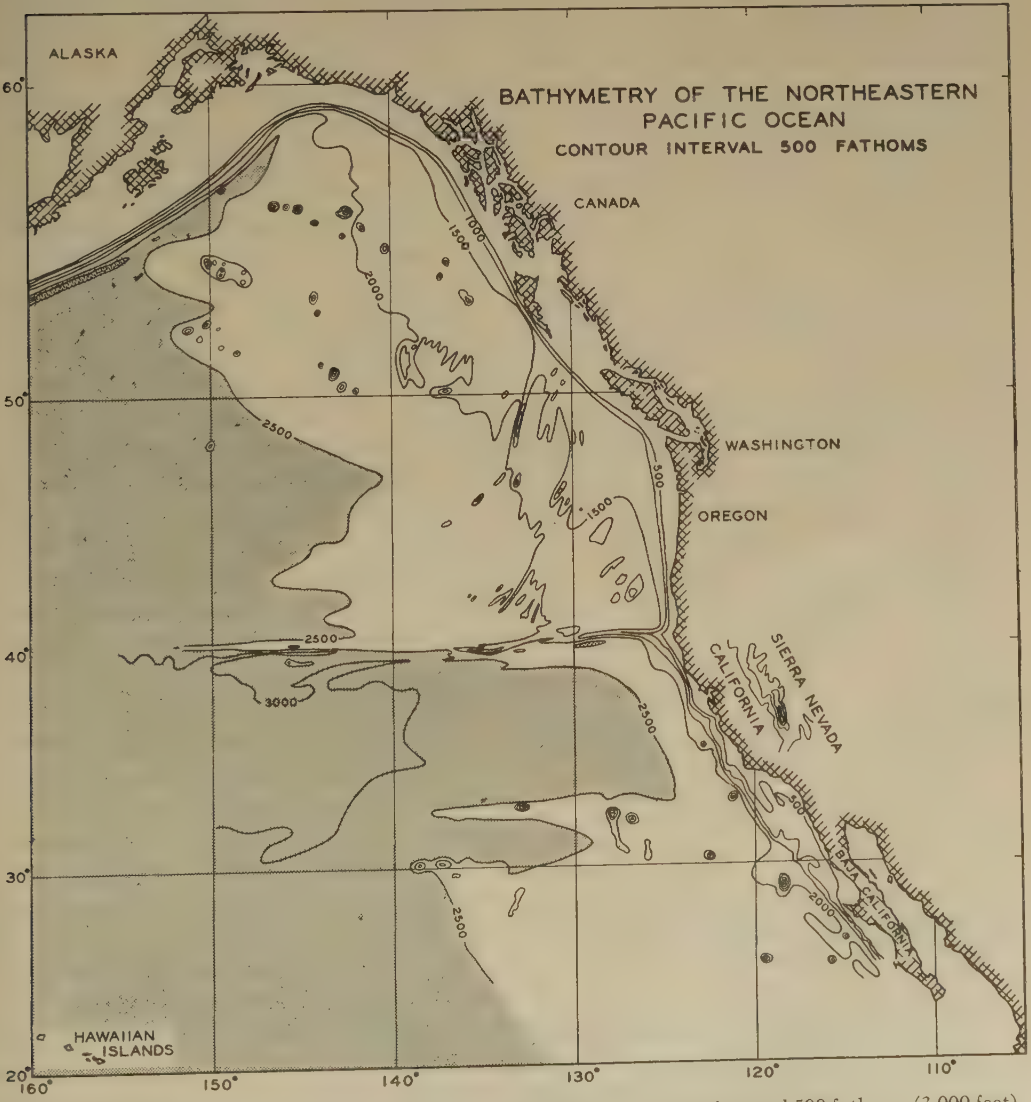

ALASKA
BATHYMETRY OF THE NORTHEASTERN PACIFIC OCEAN
CONTOUR INTERVAL 500 FATHOMS
CANADA
WASHINGTON
OREGON
CALIFORNIA
SIERRA NEVADA
BAJA CALIFORNIA
HAWAIIAN ISLANDS
1000
1500
2000
2500
1500
500
2500
3000
2500
500
2000
2500
60°
50°
40°
30°
20°
160°
150°
140°
130°
120°
110°

FIG. 2.—Bathymetric chart of the northeastern Pacific Ocean. Contour interval 500 fathoms (3,000 feet). The Sierra Nevada is contoured with the same interval for comparison with the Mendocino Scarp.

be more important than the ridge itself, because the region to the south of the ridge is about ½ mile deeper than the region to the north.

The Mexican rise and the deep area off California are likewise separated by an elongate, asymmetrical ridge, trending perpendicular to the coast. Available soundings suggest that the ridge may have a scarp, but this must remain questionable until the area is surveyed with modern equipment.

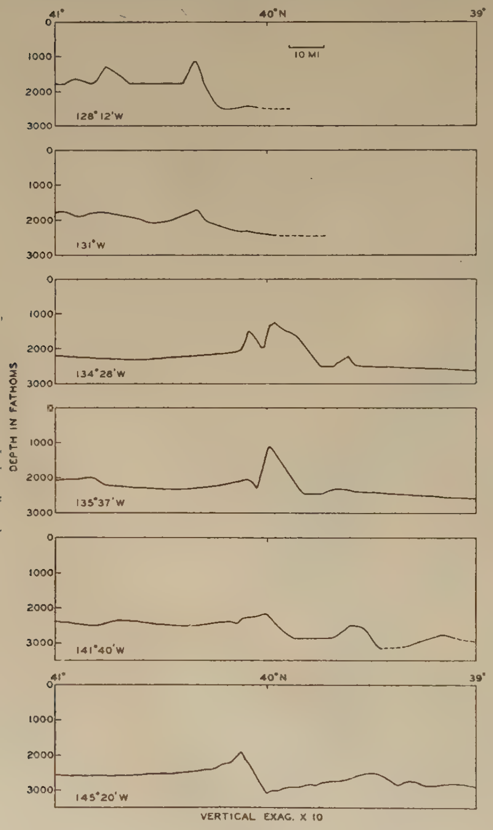


FIG. 3.—Profiles of the Mendocino Scarp

BATHYMETRY OF THE MENDOCINO SCARP AREA

The bathymetry of the Mendocino Scarp area is shown in figure 1. Profiles along west longitudes 128°12′, 131°, 134°28′, 135°37′, 141°40′, and 145°20′ appear in figure 3. Details of the bathymetry are self-evident but will be discussed briefly in order to emphasize certain features. It should be borne in mind that the sounding lines crossing the Mendocino Scarp are 10–70 miles apart and that between the lines the topography is unknown. Because of the wide spacing, all the contours might properly be dashed to indicate uncertain positions. However, the contours make sharp bends, and even with a contour interval of 200 fathoms (1,200 feet) they are bunched together in many places; so dashed lines would be very difficult to interpret. The writers have made the contours solid for ease of reading, but the positions of almost all the soundings used in making the chart are shown in figure 1, and the reader may judge for himself the accuracy of the positions of the contours and the possibilities of other interpretations of the bathymetry. The only sounding positions omitted from the chart are a few on the very tops of ridges and seamounts. It was found that the position dots or sounding-line dashes could be confused with contour lines where the lines are relatively crowded on steep slopes.

The portion of the Mendocino structure nearest the coast is the Gorda Scarp (Shepard and Emery, 1941), which is a north-facing, straight scarp about 75 miles long, with a maximum height of about 6,000 feet. The maximum slope is about 15°, and the average is about 3° (Kuenen, 1947).

The great south-facing scarp begins about 75 miles from shore. Between 75 and 200 miles from shore (longitude 126°05′ W. to 128°50′ W.), five crossings and one parallel line indicate a relatively simple, asymmetrical ridge, with a much higher and slightly steeper scarp on the south side. The scarp has a maximum height of 10,500 feet and a maximum average slope from top to bottom of 8°–9°. The line of soundings along the crest of the scarp shows that the crest is irregular and suggests that the scarp may be dissected by submarine canyons, although the irregularities may have some other origin.

Six sounding lines show a very different type of scarp between 200 and 380 miles from shore (longitude 128°50′ W. to 132°45′ W.). The ridge and scarp are complicated by the intersection of a northeast-trending lineation which appears to be a continuation of the lineation of the ridges lying to the north. The maximum average slope is only a few degrees in most of this section. The maximum height is 8,400 feet, but it decreases to 3,300 feet in the western part, where the scarp has less relief than anywhere else along the 1,200 miles of its length which have been surveyed.

From 380 to 560 miles from shore (longitude 132°45′ W. to 136°40′ W.), the main scarp bends southwest for about 50 miles, where it takes a trend slightly north of west. The ridge is asymmetrical, but in this area it is steeper, although not so high, on the north side instead of on the south, as it is in all other areas of the scarp. A second, smaller ridge lies parallel to the main ridge on the north side. The two ridges are separated by a deep, narrow trench which has some local depressions. The maximum height of the scarp in this section is 8,580 feet, and the maximum average slope is 8°–9°. The north side of the main ridge has a maximum height of 7,560 feet, and an extraordinary maximum average slope of 28°. About 100 miles north of the main scarp are many northeast-trending ridges with an average height of 1,800 feet and an average width of 5–10 miles. Several ridges lie south of the main scarp and trend parallel to it. They are asymmetrical and rise abruptly from the otherwise flat sea floor. Locally these ridges have slopes of 25°–30°.

Twelve crossings by the "Horizon" and three spot sounding lines show a remarkably simple scarp from 560 to 1,200 miles from shore (longitude 136° 40′ W. to 150°00′ W.). The scarp has a maximum height of 8,420 feet, but along most of this section the height is about 5,000 feet. The maximum average slope is about 9°–10°; the "Horizon" fathograms, however, show how misleading average slopes may be. On two crossings, portions of the scarp, 1,000 feet high, were found to have slopes of 18°–24°. Paralleling the Mendocino Scarp to the south is an elongate, partly depressed deep, with a very flat floor about 10 miles wide. South of this deep is a wider, parallel, asymmetrical ridge which is steeper on the north side; it is about 2,500–3,000 feet high in most places, but one seamount rises 6,200 feet above the surrounding sea floor.

Returning from Kodiak to San Diego, the "Horizon" crossed a scarp at 39°06′ N., 154°30′ W., which drops from 2,390 fathoms to 3,000 fathoms in 3 miles. It is about 200 miles west and 60 miles south of the outermost known part of the Mendocino Scarp, but may be connected to it.

TECTONIC INTERPRETATION OF THE SUBMARINE TOPOGRAPHY

SEISMICITY OF THE MENDOCINO SCARP AREA

In a published discussion accompanying the first description of the scarp (Murray, 1939), N. H. Heck commented on the possibility that the Gorda Scarp marks an extension of the San Andreas fault. Shepard and Emery (1941) also noted this possibility and discussed in detail the evidence for horizontal and for vertical movement. Earthquake epicenters, which accompany the San Andreas fault on land, extend out to sea at Cape Mendocino in a band with a trend to the northwest (fig. 4). Byerly (1937, 1938, 1940) has found that the distribution of the first motion of the submarine earthquake of July 6, 1934, "... combined with knowledge of the general faulting trends of the region, leads to the conclusion that the earthquake was caused by movement on a fault bearing about N 40° W, and dipping about 84° northeasterly." The Pacific side of the fault moved to the north relative to the continental side. The evidence of the strike and initial movement of one submarine fault and the general trend of a band of epicenters suggest that the San Andreas fault trends to the northwest from Cape Mendocino and does not bend to the west to follow the Mendocino Scarp. A number of depressions, which appear anomalous in relation to the surrounding northeast-trending ridges and troughs, lie in a narrow band with the same trend and position as the band

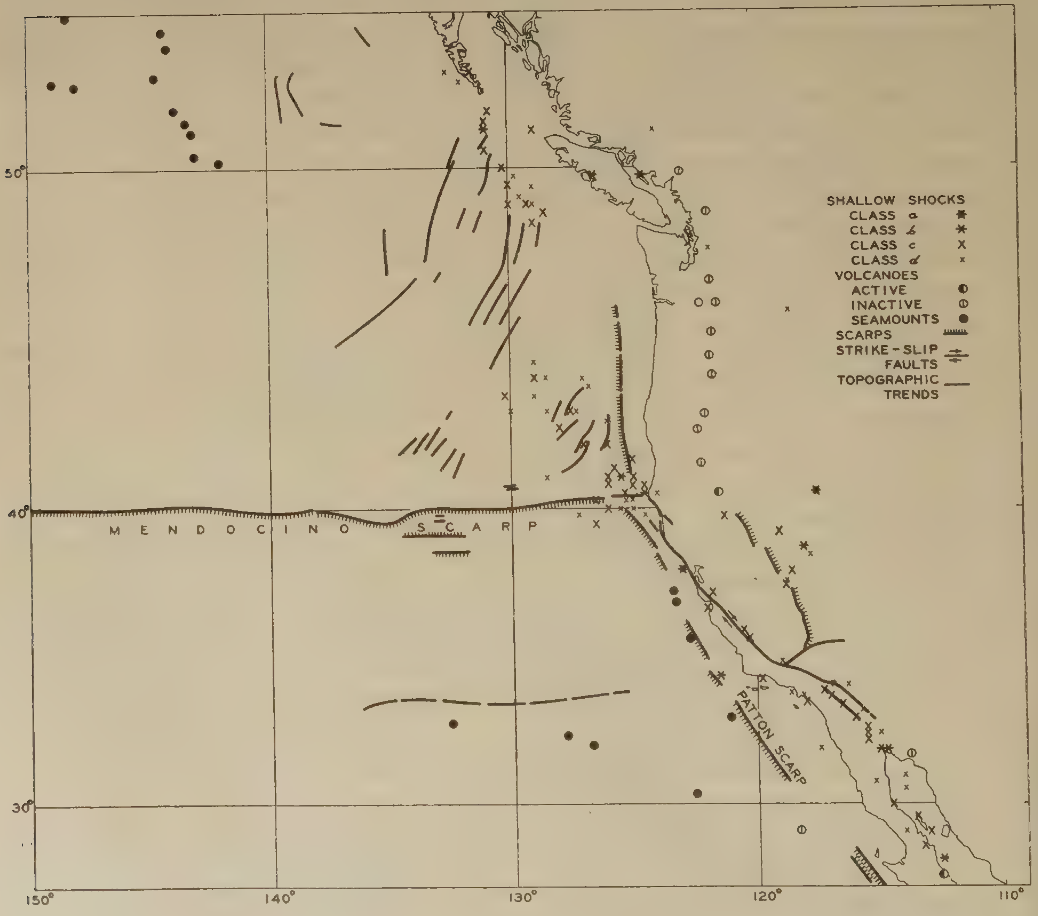

50°
40°
30°
150°
140°
130°
120°
110°
MENDOCINO SCARP
PATTON SCARP
SHALLOW SHOCKS
CLASS a ✱
CLASS b ✳
CLASS c X
CLASS d x
VOLCANOES
ACTIVE ◐
INACTIVE ⦶
SEAMOUNTS ●
SCARPS
STRIKE-SLIP FAULTS
TOPOGRAPHIC TRENDS

FIG. 4.—Tectonic pattern of the area around the Mendocino Scarp. Data on location and magnitude of earthquake epicenters from Gutenberg and Richter (1949).

of epicenters. Such depressions are commonly associated with the San Andreas fault on land.

ORIGIN OF THE MENDOCINO SCARP

No theory of the origin of the whole Pacific Basin gives a clue to the origin of the Mendocino Scarp, because none provides for the existence of a long scarp with a westerly trend in the northeastern Pacific area. Any speculation regarding the origin must draw on geophysical observations in the area, on regional tectonics extrapolated from shore, and on interpretation of imperfectly known topography; consequently, the most definite conclusions possible are nothing more than working hypotheses. A few hypotheses will be outlined and tested, but the testing will be brief, because few facts are available for the purpose. It might be taken for a fact, for example, that the Mendocino Scarp is very simple and straight; and conclusions as to origin might be based on that "fact." All that is known about the topography in this respect is that the scarp appears to be straight between widely spaced sounding lines. A similar spacing of sounding lines across the west face of the Wasatch Mountains would also show a long, straight, simple scarp instead of the complexly branching group of faults and scarps which has been found by more detailed mapping.

A few very large-scale features of the topography are firmly established by the soundings. An adequate hypothesis of the origin of the scarp should also explain these related features:

1. The sea floor for hundreds of miles to the south of the scarp is much deeper than for hundreds of miles to the north.
2. The scarp is the southern slope of a long asymmetrical ridge, and other asymmetrical ridges are parallel to the scarp on the north and south.

Among the many possible origins of the Mendocino Scarp and its associated topography, three seem worthy of consideration as working hypotheses:

1. The scarp marks the transition between "continental" rocks on the north and much more basic rocks on the south and is analogous to a continental slope.
2. The scarp marks a reverse fault produced by a north-south compression.
3. The scarp marks a strike-slip (transcurrent) fault.

"Continental slope."—The deep portion of the sea floor south of the scarp has an area of roughly 350,000 square miles. The uniformly shallower sea floor to the north has an area of more than 1,000,000 square miles, or about one-third the size of the United States. Such large areas probably are in isostatic equilibrium, and the difference in depth on the two sides of the scarp probably reflects a difference in density of the underlying rocks. Evidence from other sources supports this conclusion. Gutenberg and Richter (1935) state that the propagation of seismic waves in the Pacific area between northern California and Alaska indicates that the area is "continental" in nature and seismically is not a part of the Pacific Basin. The deeper area off central California appears to be a normal part of the basin.

Recent geophysical investigations (Raitt, 1949, and oral communications) show that the Mohorovicic discontinuity is uniformly about 5 km. below the sea floor of the northeastern Pacific between San Diego and Hawaii and that from 10 meters to a possible maximum of 700 meters of "sediment" lie above the simatic[2] layer (velocity 6.7 km/sec).

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[2] The term "sima" is used in the sense in which Gutenberg (1951) has recently defined it. It applies to crustal rocks which have a seismic velocity of between $6\frac{1}{4}$ and 8 km/sec and a density of about 3.0

The large area that Raitt studied off Baja California is, on the average, about 200–300 fathoms shallower than the deep sea floor off central California. Assuming isostatic equilibrium, a sima density of 3.0 gm/cc, an ultra-sima density of 3.3 gm/cc, and a negligible thickness of sediment, the difference in depth between the sea floor off central California and that off Baja California would be about 250 fathoms if the former region were devoid of sima. This agreement with the observed difference in depth suggests that off central California the sima is at most very thin. The relatively shoal depth of the sea floor north of the Mendocino Scarp, in turn, suggests that the sima is about twice as thick (10 km.) as it is off Baja California if the structure in the two areas is otherwise similar.

The writers do not intend to imply in the foregoing paragraphs that a portion of North America has subsided off Oregon and Washington. The depth of roughly 2,000 fathoms does not indicate that there is a sialic layer comparable to the layer under the continents; nor does the seismic evidence indicate such a layer (Gutenberg, oral communication). Moreover, no truncated seamounts (guyots) have been found off Oregon or Washington, nor has any other direct evidence of relative subsidence.

Granting rocks of different density to north and south, the Mendocino Scarp corresponds to a continental slope in position and relief, although not in depth below sea-level. A large submarine scarp recently reported by Tolstoy (1951) separates the terraced zone of the Mid-Atlantic Ridge from the deeper foothills and the "2,850-fathom plain" of the North American Basin. This scarp is as much as 8,100 feet high, and it lies on one side of a long, somewhat asymmetrical ridge. It resembles the Mendocino Scarp, and it may be another deeply submerged "continental slope"—dividing the Mid-Atlantic Ridge from the deeper sea floor of the Atlantic Ocean.

The Mendocino Scarp probably was formed in the same way as a continental slope. However, the origin of continental slopes is controversial, perhaps because there are several different origins. An initial slope must exist at the boundary between a high continent and the low sea floor, but the present continental slopes may be due to faulting or folding or deposition of sediment along the initial slope. The elongate, asymmetrical ridges in the vicinity of the Mendocino Scarp suggest that faulting of some sort has produced the present topography. The possible nature of the faulting is discussed below.

Reverse Faulting.—The general tectonic pattern of California may extend to the neighboring sea floor and thus provide a clue to the origin of the Mendocino Scarp. Faulting in southern California can be described in terms of a north-south compression (Gutenberg and Richter, 1949) which has produced many oblique, strike-slip shears, notably the San Andreas fault, and east-west reverse and thrust faults in the Transverse Ranges. Figure 5 shows a diagram of the forces acting in the vicinity of Cape Mendocino, assuming a dominant north-south compression. Whether these forces also act on the deep sea floor is uncertain, and it may be unreasonable

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gm/cc. Petrologically, these are basalts and gabbros. Less basic rocks are called "sialic rocks" (density about 2.7 gm/cc and seismic velocity less than $6\frac{1}{4}$ km/sec), and more basic rocks are called "ultrasimatic" (density about 3.3 gm/cc and seismic velocity 8–$8\frac{1}{4}$ km/sec).

to extrapolate them 1,200 miles to the outermost known portion of the Mendocino Scarp. However, Byerly (1940) believes that the San Andreas fault trend extends onto the deep sea floor, and Shepard and Emery (1941) have related the orientation of Davidson and San Juan seamounts off California to the tectonic pattern on the continent. Far beyond the known end of the Mendocino Scarp, the movement on the major faults on the western side of the Pacific is such that the oceanic area appears to be moving north relative to the continent (Gutenberg and Richter, 1949), suggesting that the same north-south compression is acting on both sides of the ocean.

If the Mendocino Scarp is undergoing a north-south compression, the scarp may be the trace of a reverse or thrust fault. Compressional faults on land typically have very irregular traces, unlike the Mendocino Scarp; but much of this irregularity results from prefaulting relief or postfaulting erosion. Granting an initially gently sloping, smooth sea floor and little erosion, the trace of a reverse or thrust fault might appear straight if surveyed on only a few widely spaced lines. The asymmetrical ridges could be formed directly as a result of reverse faulting. However, the present slope of the Mendocino Scarp is toward the south, and a reverse fault would dip toward the north. Consequently, sliding and slumping would be required to produce the present scarp. The debris should form an alluvial apron at the base of the slope, but none was observed on any of the "Horizon" crossings.

Any evidence which suggests that a north-south compression is acting in the northeastern Pacific area as well as in California increases the possibility that the Mendocino Scarp has been produced by reverse faulting. The northeast-trending ridges can be interpreted as giving such evidence. Figure 5 shows that the acute angle between the ridges and the general trend of the San Andreas fault is approximately bisected by the presumed north-south compressional forces. The geometry suggests that the ridges mark a set of shear faults which are complementary to the San Andreas fault.

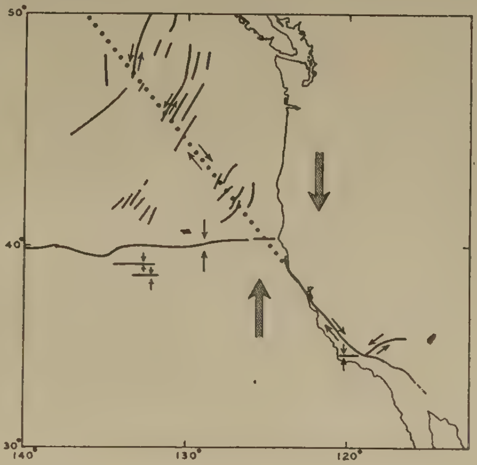

FIG. 5.—Mechanical interpretation of faulting and topography in the vicinity of the Mendocino Scarp. A north-south compression is assumed.

E. M. Anderson (discussion following Kennedy, 1946) states that, according to dynamical theory, strike-slip shear faults normally should occur in complementary classes symmetrically disposed at angles of about 25° on each side of the compression which produces the shears. He notes that good examples of this relation are found in the Santis Mountains and that a few strike-slip faults complementary to the Great Glen fault have been found in Scotland. The approximate angle between the ridges and the San Andreas fault (extended) ranges between 50° and 85° and averages about 65°. These angles are somewhat larger than the values observed by Anderson, but any angle less than 90° is mechanically possible. The hypothesis of complementary shears appears to explain the otherwise anomalous trend of the ridges. The shoal depths of individual mountains rising from these ridges and the general trend and location of the mountains suggest that they were produced by the west-coast Plio-cene-Pleistocene orogeny (Menard and Dietz, 1951). However, these ridges trend northeast, and the dominant trend of ranges and major faults produced by the same orogeny on land is northwest. It is not clear why the northeast shears should be prominent on the sea floor and not on the continent. In Scotland the development of northeast shears is favored by the general "grain" of the rocks (Kennedy, 1946), and few northwest shears are formed. Perhaps the "grain" in California favors the northwest shears, and the "grain" in the ocean basin favors the complementary ones. Figure 4 shows the more prominent northeast-trending ridges, and none are located west of about longitude 137° W., but low ridges with similar trends can be found on unpublished U.S. Coast and Geodetic Survey sounding lines as far west as longitude 155° W. A north-south compression appears to have acted across the full length of the Mendocino Scarp, if these ridges are along shears produced by such a compression.

Strike-slip faulting.—In a general way the scarp is very long and straight and has the appearance of a great strike-slip fault trace. However, many types of faulting produce traces which are straight in a general way. Strike-slip movement becomes probable if the fault is mapped in detail for long distances and is found to have no small sharp bends. The soundings in the vicinity of the Mendocino Scarp are spaced too widely to justify any conclusions regarding details of the trend of the scarp; therefore, the generally straight trace is by no means positive evidence of strike-slip movement.

Considered by itself, strike-slip movement could not produce a scarp about 1 mile high and 1,000 miles long, but appreciable vertical movement has occurred on both the San Andreas fault (Wallace, 1949) and the Great Glen fault (Kennedy, 1946), although the dominant movement on each is strike-slip. Neither of these great faults lies along an asymmetrical ridge, but elevations and depressions are rapidly leveled out by erosion and deposition on land, whereas they appear to be preserved in the deep sea for much longer periods.

The close juxtaposition of the very long, straight, strike-slip San Andreas fault and the very long, apparently straight Mendocino Scarp is suggestive of similar origin. Although the seismic evidence indicates that the San Andreas fault at present continues to the northwest from Cape Mendocino, it is possible that in the past the fault bent to the west and formed the Gorda and Mendocino scarps. Figure 5 shows that this possibility is remote because the very forces which produce a strike-slip shear in the direction of the San Andreas fault also produce a compression with no strike-slip component along the Mendocino Scarp.

CONCLUSIONS

The surveys by the Scripps Institution of Oceanography research vessel "Horizon" have served to tie together earlier spot soundings and to prove that a scarp extends west for more than 1,200 miles from Cape Mendocino, California. The scarp varies in height and is about 10,500 feet high at 70 miles offshore, and about 8,400 feet high at 1,000 miles offshore. The average maximum slope from top to bottom of the scarp ranges between 7° and 10°; but portions of the scarp 1,000 feet high have slopes as great as 18°–24°. The scarp lies on the south side of an elongate ridge which has a gentle slope to the north in most places. Other elongate sloping ridges with a scarp on one side lie parallel to the Mendocino Scarp both to the north and to the south.

The San Andreas fault appears to trend to the northwest from Cape Mendocino instead of bending to the west to follow the Gorda and Mendocino scarps. The scarp probably has formed along the contact between less dense rocks on the north and denser rocks on the south; it appears to be analogous in position and relief to the continental slope. The present topography of the scarp and of the associated long asymmetrical ridges may be due to reverse or strike-slip faulting along the initial "continental slope."

The outlines of the topography in the vicinity of the Mendocino Scarp are known only from the most generalized reconnaissance. Future surveys may find the details of the scarp to be far more complex than they appear at present. More parallel tilted blocks may be found, particularly to the south. If the foregoing discussion serves to focus interest on the northeastern Pacific Ocean as an inviting area for future geophysical and geological exploration, the writers will have realized much of their purpose in presenting this report.

ACKNOWLEDGMENTS.—The U.S. Navy Hydrographic Office and the U.S. Coast and Geodetic Survey furnished information on unpublished soundings which made it possible to prepare a bathymetric chart of the Mendocino Scarp. Moreover, the "Horizon" would not have surveyed in the area if reconnaissance soundings by ships of these two organizations had not given some indication that a scarp existed. The writers are informed by H. H. Hess that the U.S. Coast and Geodetic Survey soundings in this area were compiled by the late H. W. Murray and that he had in mind a new paper on the Mendocino Scarp at the time of his death. J. F. Frautschy and L. L. Garrison, on the first survey by the "Horizon," and ~~J. D.~~ Isaacs, W. S. Wooster, J. Barandiaran, C. V. Simmons, A. C. Smith, and H. B. Stewart, on the second survey, all co-operated in monitoring the fathometer. Captain J. L. Faughn, of the "Horizon," did the detailed navigation with Loran and star fixes which gave the surveys meaning. Roger Revelle, who led the expedition to the mid-Pacific, encouraged and helped to organize the first survey.

M. P. Billings, J. P. Buwalda, H. H. Hess, F. B. Phleger, and F. P. Shepard have been kind enough to read a preliminary draft of the manuscript—based on the first survey alone—and to make suggestions for its improvement.[3]

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[3] Eight months after the first survey and 2 days after the preliminary (then presumed final) draft had been forwarded to the editor, Mr. Warren Wooster informed the writers that the Scripps Institution of Oceanography was organizing an expedition to northeastern Pacific waters which would

Cruise VII of the "Carnegie" during 1928–1929; Oceanography—I-B, Observations and results in physical oceanography: Carnegie Inst. Washington Pub. 545, 315 pp.

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have time for a resurvey of the Mendocino Scarp. Lest this sort of thing should continue year after year, the present draft of the manuscript is being written at sea only a few days after completion of the second survey.

MARINE LEPTOPEL, ITS RECOVERY, MEASUREMENT AND DISTRIBUTION[1]

By

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ABSTRACT

Leptopel, the colloidally or otherwise finely particulate organic and inorganic detritus suspended in natural bodies of water, varies in chemical composition and in relative quantities with reference to depth, latitude and proximity to land. The leptopelic material may be quantitatively recovered by passing the water through an ultrafilter of inert, insoluble adsorptive powder. Apparatus has been designed to so recover such samples *in situ* at various depths.

Leptopelic organic matter is present in rich concentrations in the feces of filter-feeding animals, which rely upon a constant supply of it as a source of nutrition; it is present also in marine slicks, especially in association with the surfaces of temporarily entrapped fine silt particles. Fine bottom deposits in regions near shore adsorb considerable quantities of organic detritus as well, while larger inorganic particles, such as sand, furnish less surface per unit of mass for physical attachment. Far smaller quantities of suspended organic matter have been recovered from deep water samples than from those near the surface. Feces from the California mussel, a detritus-feeding filterer, and leptopel from coastal slicks have yielded considerable proportions of organic nitrogen.

Emphasis is given to the significance of organic leptopel in biochemical cycles of the sea, involving the release of inorganic nitrogenous and phosphatic molecules by bacteria, the reassimilation of these soluble molecules by phytoplankton, and the *a priori* correlation between amounts of leptopel and populations of living communities.

INTRODUCTION

Oceans, estuaries and inland bodies of water contain varying amounts of suspended *leptopel*, which is composed of finely particulate dispersed mud or sludge of organic and inorganic composition (λεπτο-, fine, thin: πηλος, mud or clay). Such materials, ranging in size from finely colloidal micelles to minute visible particles and including intimately associated micro-organisms such as bacterial cells, will vary in quantity and in chemical constitution with reference to latitude, depth, season and proximity to land.

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[1] Contribution from the Scripps Institution of Oceanography, University of California, New Series No. 568.

Reprint from SEARS FOUND. JOURN. MAR. RES.

Leptopel may be properly regarded as an attenuated hydrosol, the colloidal micelles of which, due to their constituent organic matter, may readily become somewhat concentrated at the water surface and at water-solid interfaces, there reducing the interfacial tension in accordance with the important principle first delineated by Willard Gibbs. At the surface of relatively quiet waters, the aggregations of leptopelic material may constitute extensive thin floating scums or slicks, readily observable by their contrasting optical properties. These effects are generated through diminution of the surface tension, rendering the water surface more elastic and resulting in substantial reduction in the height of the capillary waves (Ewing, 1950; Schmidt, 1936; Hardman, 1941).

The marine colloidal matter, when adsorbed to solid surfaces, such as those of submerged rocks, pilings, ships' hulls, sand or finer sediments, may assume the form of curds or of a more or less continuous semiliquid gel, muddy slime, or *pelogloea* (from πηλος + γλοια, slime, gum or oil). Sapropel is a special accepted term applied to the soft thin carpet of sludge or mud, rich in organic matter, lying upon some areas of the ocean floor.

It is manifest that the chemical, biological and sedimentational features, as well as the optical and surface studies in the realm of hydrography, must of necessity include serious consideration of leptopelic substances. The richness of bacterial flora, the production of soluble compounds of nitrogen, phosphorus and sulphur and their availability as plant nutrients, and indeed the level of general biological productivity, all must be intimately associated with the quantities of unorganized organic matter present in surrounding waters (cf. Keys, Christensen and Krogh, 1935). The physical and chemical character of sediments and the biochemical reactions occurring in them must vary greatly in accordance with the amounts of organic detritus adsorbed to the component silt, clay or sand.

Of salient interest to the marine biochemist is the direct utilization of finely particulate organic matter as a food by countless species of animals, whether by filtering the leptopel from the water with cilia, mucus-sheets, sieves, setae, or combinations of any of these, by scraping or sucking the pelogloea from solid surfaces, or by swallowing masses of whole sand, mud or sapropel at the shore line or at greater depths. Regions of relatively high leptopel concentration (e. g., near areas of river mouths, of sewage outfalls or of terrestrial run-off, or at gradually sloping rocky shores) will be expected to harbor the more dense populations of animals, including not only those species which subsist directly upon the finely divided organic matter but various predatory forms as well (e. g., sea-stars, larger crustaceans, carnivorous mollusks and fishes) which devour the whole bodies or the gametes of herbivores and detritus-feeders (Fox, 1950).

Inorganic materials, suspended in the sea or floating on its surface, carry attached organic substances. For example, in tide pools formed in the sand about the pier pilings at the Scripps Institution and open to intermittent exchange of water at low tide, flakes of mica and other sand components float upon the water surface. Such material, collected upon a fine filter-membrane and dried overnight in an oven at temperatures reaching 120°, has shown, on ashing, that there are losses of from 1.07 to 1.32% in weight, representing the approximate amount of adsorbed organic matter (cf. beach-sand; Fox, Crane and McConnaughey, 1948).

Again, analyses of feces from a marine detritus-eating filter-feeder, the California mussel (*Mytilus californianus*), throw further light upon the composition of leptopelic marine detritus. Such material has shown an average ash content of 69.1%. Organic nitrogen (by Kjeldahl analysis) shows an average value of 1.1% which, when multiplied by the conventional factor of 6.25, gives approximately 6.9% protein in the whole feces or some 22.3% protein in the total organic matter in the feces. Lipids may amount to as much as 12%, or 38.7% of the organic fraction, leaving about 39% as carbohydrates or other components (cf. Fox and Coe, 1943).

Kalle (1946) has reported that yellow, blue-fluorescing ulmic acid-like derivatives, arising from such materials as decaying wood, peat, etc., reflect, by their relative concentrations, the quantities of terrestrial organic matter introduced by runoff into coastal waters.

Suspended materials in the English Channel have been studied by Armstrong and Atkins (1950). Some of the suspended solids were recovered by collecting water in wooden vessels and by passing large volumes of it through filter paper and through "Gradocol" membranes. The coarser particles retained in typical analyses yielded about 1 mg/l. Residual colloidally dispersed material yielded traces of ash, involving about 60% SiO_2 and some 13% Fe_2O_3. The Tyndall beam was observed to persist in filtrates which had passed membranes of 0.2μ average pore diameter.

Dried, ignited residues reportedly ranged from 2.77 to 0.45 ppm, while the organic matter, measured in a few analyses by drying at 100°, amounted to about 1.5 ppm. While the porosity of the filters used by Armstrong and Atkins suggest that recovery was incomplete, the persistence of the Tyndall beam in the filtrates bearing out such a conclusion, the data agree rather well with the results obtained at La

Jolla. The British workers found in the ash of their recovered solids the following components in respective proportions: SiO_2, 17 to 55%; Fe_2O_3, 3 to 28%; Al_2O_3, 1 to 20%; and $CaCO_3$, 9 to 70%.

Comparative turbidimetric measurements of sea water samples have been conducted by Jerlov (1951), who employed the relative intensity of Tyndall scattering for following water movements in estuaries and through straits.

Investigations of marine leptopel are being pursued with the expectation that quantitative data may be gathered relative to the amounts and variations in colloidal and other particulate organic matter according to depth, latitude, season, and proximity to shore. Such data, it is hoped, may afford a correlative parameter that will supplement surveys of microplankton populations, studies of concentrations of dissolved oxygen, phosphate, nitrate and silicate, and observations of similar factors associated with marine biological productivity.

The presence of leptopel may be demonstrated by the gray or bluish Tyndall cone that is produced when a glass vessel (preferably a Florence flask) filled with sea or tap water is illuminated in a darkened room by a bright light (e. g. from a carbon arc) which passes through an adjustable slit or iris diaphragm and which is brought to a focus within the body of the fluid by means of a supplementary lens. The Tyndall cone is intensified by minimizing stray light and by placing the flask against a dark background; or better, black paint may be applied to the outer half of the flask's surface opposite the viewer.

After all colloidal and other finely suspended matter has been removed by passing the water through a sufficiently fine ultrafilter and collecting it in a scrupulously clean container, under appropriate illumination the water now manifests only the quality of a barely perceptible, soft blue-violet Tyndall cone which is given by twice-distilled water, as described by Lord Rayleigh and by Wood (1934, Chap. XIII). This so-called Rayleigh scattering is characteristic of pure air, pure water, and other homogeneous fluid molecules.

MATERIALS AND METHODS

(a) *Collection by Adsorption.* The finely suspended matter may be quantitatively removed by passing the aqueous system through a short layer of finely powdered adsorptive inorganic material. Selection of an insoluble and relatively inert adsorbent permits quantitative investigations to be carried out on the particulate materials. For this purpose, various finely powdered or somewhat gelatinous compounds have been employed, including MgO, $MgCO_3$, Fe_2O_3, $CaCO_3$, $Mg(OH)_2$, kaolin, talc and cellite (or Hyflo Super-cel, a refined diatoma-

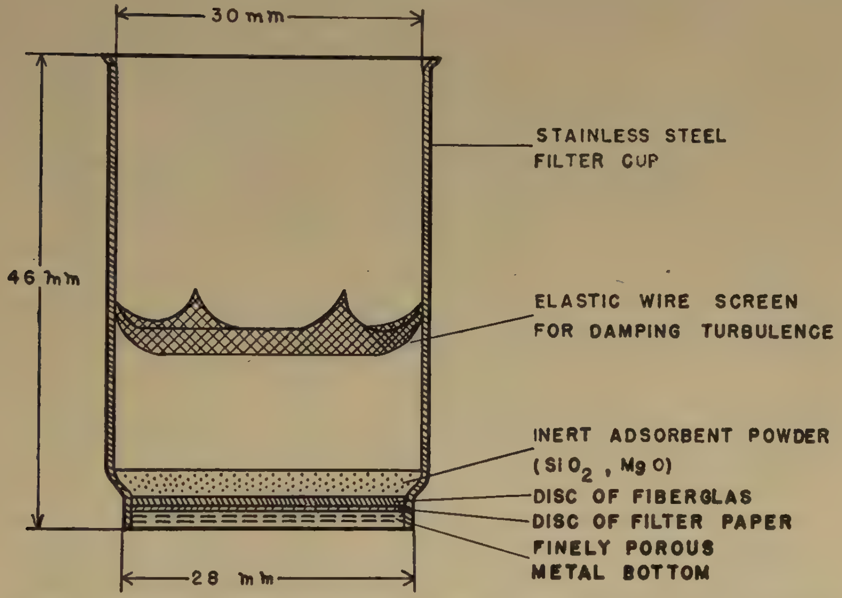
30 mm
46 mm
STAINLESS STEEL FILTER CUP
ELASTIC WIRE SCREEN FOR DAMPING TURBULENCE
INERT ADSORBENT POWDER (SiO_2, MgO)
DISC OF FIBERGLAS
DISC OF FILTER PAPER
FINELY POROUS METAL BOTTOM
28 mm

Figure 1. Diagram of stainless steel filter crucible, containing glass-cloth pad supporting inert adsorbent powder; ready for use.

ceous earth, substantially pure SiO_2). Repeated investigations have been carried out on the complete adsorptive removal of finely dispersed protein micelles from aqueous systems, e. g., dilute sols of gelatin, egg albumin, hemoglobin, the latter two forming micelles of very small size (McBain, 1950: 128–129), or mixed fresh materials such as breis of mussel tissues. A separate report by Fox, Kittredge and Oppenheimer will deal with the quantitative adsorption achieved with the use of a mixture of equal weights of pure MgO and SiO_2 (Hyflo Super-cel).

It is necessary to employ amounts of the adsorbent in such excess as to assure quantitative adsorption of all particulate materials. Since most natural waters are extremely dilute disperse systems, the required excess of adsorbent is easily achieved by the method outlined below.

One or two grams of powder (equal weights of MgO and cellite) packed into a filter-cup (30 mm diameter) provide an operating column of adsorbent material some 6 to 8 mm high, which is sufficient to adsorb in a thin layer (1 to 2 mm) all colloidal material commonly encountered in large volumes of sea water. Standard glass crucibles with fritted glass bottoms are suitable in the laboratory, but for work at sea, similar cups of stainless steel are used because of their ruggedness (Fig. 1).

The clean porous cup is fitted into its adaptor, which is then inserted into the mouth of a filter-flask, preferably a Fisher filtrator (see below). To keep the fine powder from clogging the pores, a loosely fitting disc of No. 50 Whatman filter paper is laid on the floor of the cup, after which the paper is moistened with distilled water and drawn to a smooth coverage of the fritted area by applying gentle suction. No wrinkles should be allowed to remain in the paper, since they may serve as channels for the escape of some of the adsorbent. A disc of clean glass cloth (Fiberglas) of equal diameter is then placed over the paper disc in order to isolate the powder from this potential source of organic contamination; the glass disc is dampened and drawn by suction uniformly against its substrate in the manner previously described. Equal parts (usually 0.5 g each) of floury Hyflo Super-cel and pure finely powdered MgO are intimately mixed in a small quantity of pure distilled water (or in previously filtered, colloid-free sea water if necessary), and the suspension is poured carefully down a stirring rod onto the bottom of the filter-cup.[2]

The system is allowed to stand for about five minutes, thus providing time for most of the suspended powder to settle, after which some of the water is slowly drawn through by gently opening the vacuum line. Drawing through *all* of the water, thus exposing the filter-bed directly to the atmosphere, commonly leads to the formation of cracks and channels and to shrinkage from the walls of the cup. Should such channels occur through inadvertent exposure of the powder-cake, these should be filled with additional absorbent powder in suspension before conducting the ultimate filtration.

The preliminary filtration of reagent-water should proceed until a clear filtrate is obtained; this is frequently achieved at the outset or after only a small volume has been delivered within the first few minutes. Filtration is then halted *gently*, i. e., by gradually opening an intake valve in the vacuum line to avoid jarring the filter-pad loose from its firm seating. The design of the Fisher filtrator provides against such a contingency.

The prepared filter is permitted to stand, filled with water and undisturbed until ready for use. When collections are to be made

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[2] In this operation a saturated solution of $Ca(OH)_2$ may be employed instead of water alone in order to provide sufficient traces of alkali to coat the adsorbing surfaces with $Mg(OH)_2$, which is generated at once upon introduction of sea water. Excessive $Ca(OH)_2$ gives rise to sufficient $Mg(OH)_2$ to clog the filter; use of the powdered lime itself is therefore to be avoided. Even the saturated $Ca(OH)_2$ solution should be omitted if a balanced sea-water filtrate is desired for a biological medium.

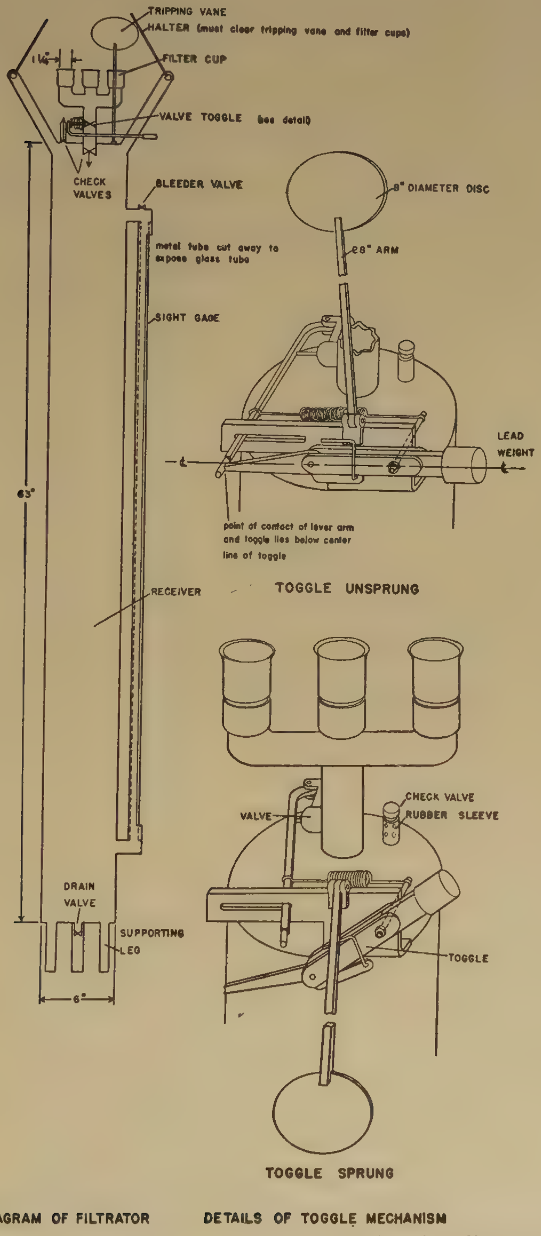
TRIPPING VANE
HALTER (must clear tripping vane and filter cups)
1¼"
FILTER CUP
VALVE TOGGLE (see detail)
CHECK VALVES
BLEEDER VALVE
metal tube cut away to expose glass tube
SIGHT GAGE
63"
RECEIVER
DRAIN VALVE
SUPPORTING LEG
6"
8" DIAMETER DISC
28" ARM
LEAD WEIGHT
point of contact of lever arm and toggle lies below center line of toggle
TOGGLE UNSPRUNG
CHECK VALVE
RUBBER SLEEVE
VALVE
TOGGLE
TOGGLE SPRUNG
DIAGRAM OF FILTRATOR
DETAILS OF TOGGLE MECHANISM

Figure 2. Diagrammatic sketches of the Scripps Subsurface Autofiltrator and of detailed parts.

from aboard ship with the use of the subsurface autofiltrator (developed by J. D. Isaacs; see Fig. 2), a stiff elastic screen of stainless steel wire is pressed into the mouth of the cup for a short distance. This is to preclude possible disturbance of the filter-bed by inrushing water following any spillage of the resident water from its cup while the gear is being lowered away. The buffering screen is omitted during laboratory operations, where cautious procedures may be assured.

Water to be transferred to the laboratory for analysis is best collected directly into clean bottles of inert water-repelling plastic material. This procedure provides against accidental breakage, affords a degree of lightness, and should minimize adsorption of the colloidal materials to the walls of the container. Such potential sources of loss may be further reduced by adding one or two grams of the powdered adsorbent to the container before or at the time of collection, provided the sample in each collecting vessel is destined for quantitative adsorptive recovery upon a single filter.

Should a delay of some hours be anticipated before water samples can be analyzed, mercuric chloride may be added to give a dissolved concentration of about 0.1 g/l; such procedure serves as a preservative against bacterial degradation of the organic matter.

(b) *The Subsurface Autofiltrator.* In operations at sea, an important requirement in the quantitative sampling of leptopelic material *in situ* at any desired depth is to minimize contact of the raw water with any save the actual filtering surface. With this in mind, several alternative operations may be considered briefly before we describe the means which have been adopted as best satisfying requirements.

(1) Pumping water from selected depths through long tubes to a filter on deck, or collecting it in wooden, glass or metallic containers for subsequent filtration aboard ship. These devices are undesirable because: The adsorption of interfacially active colloidal materials to the extensive solid surfaces would create errors; later, after repeated operations, a degree of sloughing (or desorption) of accumulated films from such devices might substantially contaminate the samples to be filtered and analyzed.

(2) The alternative use of a pump aboard ship, drawing water through a filter installed at the end of a hose paid out overside. This procedure would involve several disadvantages: It would limit the pressure gradient to a low value, i. e., the prevailing barometric pressure, minus the height of the pump above the sea surface, minus the ambient vapor pressure of the water; the additional difficulties involved in storing and handling long tubes of fairly large diameter

would limit such a system to the use of relatively coarse filters at shallow depths.

(3) Subsurface collections made with a submerged pump, designed to draw the water directly through the juxtaposed filtering medium by providing a high gradient *in situ*. Such apparatus would possess the manifest advantage of minimizing time and area of prefiltering contact for processing large quantities of water at gradients limited only by the absolute hydrostatic pressure at the depth of operation. Disadvantages in such a design include not only the necessity of supplying a source of power and a metering system but the practically unavoidable risk of contaminating the collected residues with droplets of lubricating oil from the pump. However, a unique system may be applicable to filtration of samples while the ship is underway. This would involve submergence of the instrument to desired depths with a depressor (Isaacs, 1951) and the employment of the Venturi principle to obtain the required pressure gradients. The comparatively slow rates of water passage through a fine adsorptive powder filter would permit a multiplication of Venturi units, i. e., a small unit operating in the region of high velocity produced by a larger unit. Preliminary calculations have yielded promising indications for the application of such devices.

The subsurface autofiltrator which has been developed at the Scripps Institution is of reasonably simple and rugged design and is shown in Fig. 2. It utilizes a large heavy cylindrical receiver which permits the gradient between its interior (at atmospheric pressures or evacuated if necessary) and the ambient hydrostatic pressures outside to effect filtration of the water at the desired depth. The device is not lubricated, and it requires no mechanical metering system, since the filtered water is retained and can be measured directly at the end of the operation in a calibrated sight gauge. The factors of large size and bulkiness are relatively minor, since modern oceanographic gear is adapted for ready manipulation of large and heavy equipment.

The tripping mechanism is of somewhat unique design and deserves some detailed description. The toggle is designed to preserve its balance under conditions of severe linear shock, provided there be no actual contact with the tripping device itself. This design is achieved by balancing the first moment of mass about the fixed pivot.

It is to be remembered that the moment of the notched outer arm of the toggle is only its reaction at the central pivot. Having calculated this value, we then affixed an equivalent mass at the central pivot and balanced the mechanism against gravity around the fixed pivot. With a trapezoidal outer arm of thickness t, of density ρ, of length L and of major and minor altitudes A and B respectively, the reaction of the central pivot (R_1) is:

$$R_1 = L^2 t\rho\left(\frac{A + 2B}{6}\right).$$

With an equivalent mass suspended at the central pivot, the lead counterweight is adjusted to produce a balance about the fixed pivot (see Fig. 3). The mechansim in current use has received heavy mechanical shocks without resultant tripping of the cocked toggle.

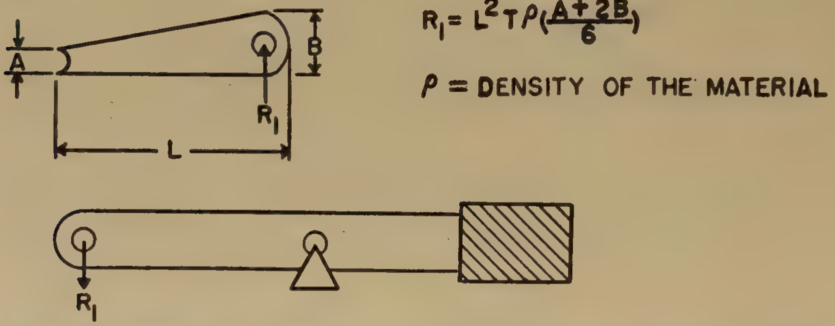

Figure 3. Representation of the forces involved in the tripping mechanism of the Scripps Subsurface Autofiltrator.

Accidental tripping of the toggle through premature falling of the vane (e. g., due to the roll of the ship or to wave action) is precluded by the length of the vane arm. The force of the arm against the toggle trigger should exceed by three- or four-fold that which is necessary to produce tripping. This requirement is readily calculated from the force relationships in the toggle (see Fig. 4).

The required thickness of the cylinder wall is calculated from the relationship:

$$P = \left(\frac{2E}{1-\mu^2}\right)\left(\frac{(t)}{D}\right)$$

where P = collapsing pressure, μ = Poisson's ratio, t = thickness of wall, D = diameter to neutral axis, and E = Young's modulus.[3]

The thickness of the glass walls of the sight gauge may be selected in accordance with similar analysis, but adequate strength is to be found in any boiler gauge material adapted to meet high pressures.

In operations at sea, the stainless steel filter cup (or each of these if two or three are employed in order to shorten the filtration time) is furnished with the powdered filtering material in the manner previously described. An elastic stainless steel wire screen is pressed firmly into position at about half the depth of each cup, which is then filled with water. The toggle is cocked and the tripping vane is attached and held in a nearly vertical position with a single band of glued paper tape (a weak junction of paper readily torn apart when wet is preferable). To preclude the filtration of any sea water before the gear has been lowered to the desired depth, the short tube or filter manifold above the valve is filled with water until very little air space remains in the adaptors.

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[3] From "Implosion of cylinders," W. H. O. I. Report (unpublished).

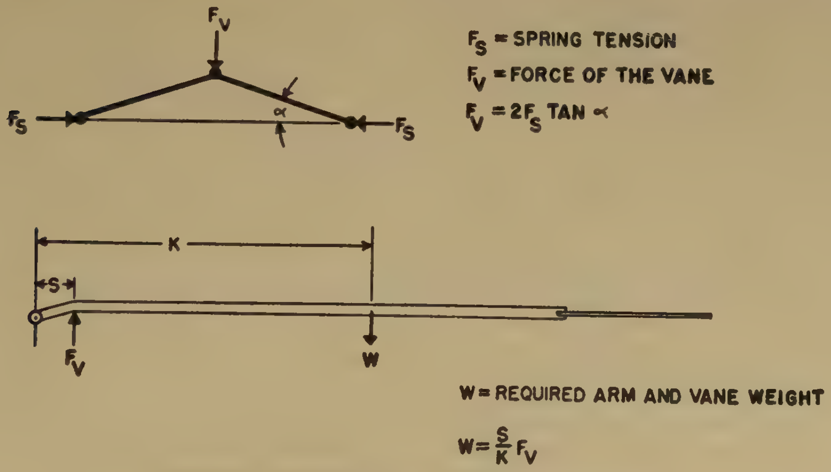

Figure 4. Diagram of force relationships in toggle.

The prepared filter cups are now fitted into the open adaptors, which are supplied with rubber sleeves. With the tripping vane held in position by hand or by weak tape, depending on the amount of freeboard of the vessel and on the rapidity of lowering, the assemblage is lowered over the ship's side and the supporting cable is paid out to permit rapid sinking until the required depth has been achieved.[4]

When the cable meter indicates the required depth, lowering is abruptly halted, whereupon the tripping vane rotates into its downward position and its arm trips the toggle; thus the valve beneath the filter manifold is opened and the passage of water is initiated through the adsorptive powder and into the reservoir below. The time required for the collection of adequate samples (ca. 20 l of filtered water in the current model) will depend upon the hydrostatic pressure of each sampling depth and upon the fineness of the powder and the length of the powder column. Suggested intervals for the collection of from 15 to 20 l are as follows:

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[4] If lowering is accomplished rapidly enough, the vane arm will not fall sufficiently to trip the toggle before immersion and descent of the apparatus serves to prevent this; should the freeboard be too great to risk abortive tripping, the single lashing with paper tape may be applied, since this will come free shortly after submergence

Depth	*Time Interval*
On surface (with evacuated chamber)	30 min.
50 m (unevacuated chamber)	20 min.
100 m	15 min.
300–1000 m	10 min.

As the instrument is raised the pressure of the expanding air within the top of the cylinder closes a check valve in the filtering manifold, thus halting filtration and precluding passage of air with destruction of the filter pad. The air now escapes through another check valve on the top of the cylinder. At the surface the volume of filtered water is recorded from the calibrated sight gauge. The filter cups are removed and the filtrator reservoir is emptied by opening the drain and bleeder valves (see Fig. 2).

(c) *Chemical Analysis.* Once the colloidally dispersed substances have been adsorbed upon a pad of inert inorganic powdered material, it is possible to determine approximate concentrations of numerous constituents in terms of milligrams per liter of water filtered. Lipid materials may be extracted with organic solvents; chlorophyll or its porphyrin derivatives, as well as carotenoids, may be similarly recovered and measured photometrically; colloidal iron oxides and colloidal phosphate may be recovered and measured by special methods. Retained organic carbon and organic nitrogen may be determined. Preliminary reports of the methods and findings regarding the latter two components are given in this paper. Discussion of other constituents will be reported elsewhere.

The organic nitrogen content of adsorbed leptopel was determined by the Kjeldahl method; the sample was completely digested with boiling conc. H_2SO_4, and the resulting NH_3 was distilled from the alkalized system into a saturated boric acid solution and measured volumetrically (from a semimicroburette in this work) by titration with dilute standard HCl, using methyl orange as indicator.

The organic carbon content was measured by a rapid titration method outlined by Waksman (1936: 404–405). The reagents used are: (1) about 0.4 N chromic and sulphuric acid solution prepared by dissolving 40 g of $K_2Cr_2O_7$ (or 32 g CrO_3) in 1 l of H_2O, to which is added conc. H_2SO_4 (sp. gr. 1.84) to give 2 l of solution when cool; (2) about 0.2 N acidic ferrous ammonium sulphate, prepared with 80 g of the salt $(Fe(NH_4)_2\ (SO_4)_2 \cdot 6H_2O)$ and 20 ml of conc. H_2SO_4/l of solution, which is ultimately standardized with 0.1 N $KMnO_4$ solution; 1 ml of the ferrous ammonium sulphate solution is taken as equivalent to 0.6 mg of organic carbon, or to 1.034 mg of humus. (3) Diphenylamine indicator prepared with 0.5 g dissolved in 100 ml conc. H_2SO_4 + 20 ml water.

Each sample (i. e., the powdered filter pad) is transferred to a 100 ml Erlenmeyer flask; to each flask is next added a considerable excess (usually 10 ml) of the chromic acid solution. After either a small funnel or a Pyrex "cold-finger" (a short round-bottomed tube of cold water, fitting the opening of the flask and covering its mouth with a flanged rim) is inserted into each flask, the contents are heated to the boiling point and kept moderately boiling for five minutes. The contents of each flask, after cooling, are transferred quantitatively into a beaker or a large flask of about 400 ml capacity which contains about 250 ml of distilled water. Care is taken to rinse into the receiver any material that adheres to the funnel or cold finger or remains in the boiling flask. Ten drops of the indicator commonly suffice to impart a distinct violet-blue color to the solution, which is now titrated with the ferrous reagent until there is a sharp change to grayish green which becomes a deeper green on standing.

Multiplying the factor 0.6 by the difference between the observed titration figure and that of the control (i. e., 10 ml of chromic-sulphuric acid solution alone, previously boiled and diluted in the same manner) yields the empirical figure for the organic carbon content of the sample.

It is to be emphasized that the quantity of chromic acid reduced will naturally vary somewhat in accordance with the condition of the organic carbon involved, e. g., the degree in which it may already have been combined to some extent with oxygen, as in carbohydrate material $(CH_2O)_n$ or alternatively in a more reduced state, as in fatty acids, hydrocarbons, long-chain alcohols, and the like (CH_3-CH_2-CH_2 . . .). The factor adopted applies to humic materials in general and has been retained throughout in the present work, since a part of our program deals with the determination of organic carbon of marine humus in sediments; it is highly probable that most samples of suspended leptopel will contain varying amounts of the relatively refractory humic material.

Table I shows a summary of quantitative findings relative to the amounts of leptopelic organic matter in marine waters and in other

TABLE I. Results of Quantitative Studies of Leptopelic and Pelogloeal Organic Matter, Collected and Analyzed in Various Ways.

Material	*Method of Collection*	*Method of Analysis*	*Organic C*	*Organic N*	*Other Material*	*Total Organic Matter*
1. Beach sand	Manual	Dry combustion				0.7%*
2. Floating mica	By aspiration	Dry combustion				a. 1.07% b. 1.32% av. = 1.2%
3. Mussel feces	Voided by freshly collected mussels	Organic matter by combustion; organic N by Kjeldahl; lipid-soluble matter by extraction with organic solvents		a. 1.02% b. 1.06% c. 1.19% d. 1.13% av. = 1.1% or 1.1 × 6.25 = 6.87% protein	Lipid-sol matter 3.7% (or ca. 12% of total organic matter)	a. 36.2% b. 30.7% c. 25.7% d. 31.1% av. = 30.9%†
4. Sedimentary component of a marine slick	In bottles, from surface, by G. C. Ewing	Wet chromate combustion of sediment				27.65%
5. Water from a slick area near shore in San Diego Harbor	In bottles, from surface, by G. C. Ewing a. turbid water from slick surface b. clear water 6″ beneath slick c. clear water from rippled surface	Organic C by wet chromate combustion of adsorbed filter residues; organic N. by Kjeldahl analysis of similarly recovered material	a. 6.77 mg/L b. 4.16 mg/L c. 5.9 mg/L C/N a. = 9.55 C/N b. = 9.25 C/N c. = 9.42	a. 0.71 mg/L = 4.44 b. 0.45 mg/L = 2.78 c. 0.63 mg/L = 3.94	mg protein/L	C × 1.8 N × 17 a. 12.20 12.05 b. 7.48 7.58 c. 10.70 10.54 av. a. 12.12 mg/L av. b. 7.53 mg/L av. c. 10.61 mg/L
6. Water from various oceanic depths off San Diego a. 9 l from 150 m, 32° 37′ N, 120° 29′ W b. 20 l from 600 m c. 20 l from 300 m d. 20 l from 100 m (all 3 samples from station at 33° 02′ N, 118° 59′ W)	Subsurface autofiltrator	Organic C by wet chromate combustion of adsorbate on Super-cel + M_gO, 1:1	a. 0.47 mg/L b. 0.14 mg/L c. 0.16 mg/L d. 0.17 mg/L			C× 1.8 a. 0.85 mg/L b. 0.25 mg/L c. 0.29 mg/L d. 0.30 mg/L
7. Water from slick areas San Diego Channel	In bottles, by G. C. Ewing and M. W. Johnson; preserved with H_gCl_2 at time of collection a. from surface b. from near bottom (ca 10 m deep) c. from surface d. just beneath surface	Wet chromate combustion of adsorbate on Super-cel + $Ca(OH)_2$, 1:1	a. 17.66 mg/L b. 19.64 mg/L c. 11.61 mg/L d. 6.71 mg/L			Org. C × 1.8 a. 31.7 mg/L b. 35.3 mg/L c. 20.9 mg/L d. 12.1 mg/L
8. Oceanic bottom mud, from station 32° 37′ N, 120° 29′ W (cf. item 6 in this table) a. 0–1 inch depth of mud b. 3–4 inch depth of mud c. 10–11 inch depth of mud	In coring sampler	Wet chromate combustion			Ash (%) H_2O (% in dried samples by difference) a. 88.29 7.73 b. 85.59 11.32 c. 85.64 10.74	Org. C. (%) Org. matter (%) (C × 1.7) 1.88 3.20 1.56 2.65 2.01 3.42

* Fox, Crane and McConnaughey, 1948.

† Fox and Coe, 1943; Fox, Updegraff and Novelli, 1944.

marine materials. It will be observed that concentrations of organic matter are relatively high in shallow waters near shore, especially in the vicinity of marine slicks (e. g., from about 7.5 to as high as 35 mg/l), while in water from considerable depths far from shore the values are relatively low (from 0.25 to 0.85 mg/l). In the data at hand there are higher concentrations of organic matter in the former than in the latter environment by some 40-fold.

Solid materials such as mussel feces or silt from a floating slick are relatively rich in organic matter, while beach sand and fine bottom sediments adsorb quantities of organic materials that yield intermediate values which are in rather good agreement with data presented by Revelle and Shepard (1939: 245–282).

It is also to be observed that the organic material recovered from both mussel feces and from a slick (items 3 and 5 respectively in Table I) were relatively rich in nitrogenous material. The four analyses of mussel feces yielded 17.6, 21.5, 28.9 and 22.7%, with an average value of 22.6% "protein," while the material from the slick gave 36.6, 36.9 and 37.1% respectively or an average figure of 36.9% "protein."

DISCUSSION

A brief review of relative masses of animate and unorganized colloidal or otherwise particulate organic matter in the sea may be of interest. The fact has been emphasized that "in any area of biological productivity, the total quantity of unorganized, raw material must considerably exceed the mass of organized living matter." (Fox, 1950; cf. also Keys, Christensen and Krogh, 1935).

Sverdrup, et al. (1942: 250–251, 912) have emphasized this point, citing the work of Krogh and of Bond (1933). While Krogh estimated that the "dissolved" organic material exceeds the "particulate" organic matter by some 300-fold, Bond's figures indicate a preponderance of only 76.9%, or some 3.3-fold of such "dissolved" organic matter over the combined amounts of net plankton and nannoplankton. Bond's investigations, carried out in waters near Friday Harbor, which are characteristically rich in phytoplankton, yielded average figures of 0.03, 0.03 and 0.20 mg-at C/l of water in net plankton, nannoplankton and dissolved organic matter respectively. These figures, multiplied by 12 to give mg of carbon, and by the factor of 2 to convert to organic matter, are 0.72, 0.72 and 4.8 mg/l. Bond's term "dissolved" naturally refers to colloidal and other suspended matter as well as such materials as may have been in true solution.

Reviewing the data obtained at La Jolla (including those presented here and by Fox and Coe, 1943) and those of Brandt (1898), we arrive at some interesting approximate ratios of living phytoplankton to unorganized organic detritus in local waters. Living phytoplanktonic organisms in waters off La Jolla may supply average amounts of organic matter such as the following:

Dinoflagellates (ca.10,000/L; 2×10^{-5} mg organic matter/cell)	0.2 mg/L
Diatoms (ca.20,000/L; 1.5×10^{-6} mg organic matter/cell)	0.03 mg/L
Bacteria (ca.45,000,000/L; 5×10^{-11} mg organic matter/cell)	0.002 mg/L
	ca. 0.23 mg/L

Now, if we take 5 mg/l as an average value for total colloidal or otherwise finely particulate organic matter, the living fraction would appear to be only some 4% of the total; but if we should adopt the figure of 15.3 mg/l (the average value of collective data in items 5 and 7, Table I), then the proportion of living cells would appear to be only about 1.5% of the total.

Marine biochemical cycles undoubtedly entail close parallelism between fluctuations in populations of microplankton and concentrations of suspended organic detrital materials. It would be unlikely that the mass of living cells, even of phytoplankton, should exceed that of suspended detritus in any area, save for relatively brief periods.

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SUMMARY

The nature, methods of quantitative recovery, chemical measurements, and distribution of organic materials in marine leptopel are discussed.

Marine detrital organic matter is relatively concentrated in solid material such as the feces of filter-feeding animals, in finer sediments on the ocean floor or in fine silt temporarily suspended in surface slicks. It shows intermediate concentrations in waters removed from

the vicinity of slicks and is recoverable in relatively low concentrations from water a few hundred meters in depth, at some distance from shore.

The quantitative determination of organic leptopel is discussed as a useful parameter in studying marine biochemical cycles, and discussion is given to the general ratio between the weight of organic matter in living microplankton and the total mass of organic substances in suspended marine detritus.

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PART PLAYED BY BACTERIA IN PETROLEUM FORMATION

BY

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PART PLAYED BY BACTERIA IN PETROLEUM FORMATION[1]

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ABSTRACT

Biochemically versatile bacteria, capable of catalyzing a good many chemical reactions, occur abundantly in recent marine sediments. Living bacteria detected in certain petroliferous formations at appreciable depths are believed to be indigenous species in a state of dynamic equilibrium with their environment.

If petroleum is formed from organic matter, it is almost axiomatic that bacteria have contributed to the process, because the organic remains of both plants and animals are susceptible to microbial modification. In recent marine sediments bacteria tend to convert organic compounds into humus and other substances approaching the elementary composition of crude oil.

Besides producing methane as an end-product of metabolism, certain bacteria synthesize small quantities of liquid and solid hydrocarbons as an integral part of their cell substance.

Anaerobic bacteria found in sediments catalyze the oxidation of molecular hydrogen with the formation of methane, hydrogen sulfide, saturated compounds, and other substances that may occur in oil fields.

Crude oil in contact with water may be slowly modified in various ways by bacterial activity.

Bacteria may contribute to the migration and accumulation of oil by promoting its liberation from oil-bearing sediments.

Although many theories have been advanced (Brooks, 1936; Skelton and Skelton, 1942) to account for the origin of oil, the reactions resulting in the formation of petroleum are still obscure. It is generally agreed, however, by petroleum geologists (Cox, 1946) that crude oil was formed from the organic remains of plants and/or animals in a marine environment at pressures mostly less that 5,000 psi, and at relatively low temperatures, the maximum being in the neighborhood of 100°C. for most oil basins.

Based upon the premise that organic matter is the mother substance of petroleum, it is almost axiomatic that bacteria and allied microorganisms must have contributed to the process, because virtually all known types of organic matter are susceptible to microbial modification in marine sediments. Moreover, microorganisms may have played a part in conditioning the marine environment by virtue of their effect on the hydrogen-ion concentration, redox potential (ZoBell, 1946a), state of sulfur, gas tension carbonate content, and other properties of sediments (ZoBell, 1942, 1943).

BACTERIA IN PETROLIFEROUS SEDIMENTS

Recent marine sediments rich in organic matter contain large numbers of living bacteria (ZoBell, 1938). Although their abundance decreases with depth (ZoBell and Anderson, 1936), significant numbers have been detected at the bottom of the longest marine mud cores that have been examined for the presence of bacteria. Rittenberg (1940) demonstrated the presence of numerous bacteria throughout the length of several cores, some of which were 350 cm long. Living bacteria have been detected in carefully collected cores taken near shore with a pile driver from depths exceeding 150 feet.

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Bastin (1926), Gahl and Anderson (1928), Bastin and Greer (1930), Ginter (1930), Ginsburg-Karagitscheva (1933), Müller and Schwartz (1949), and several others have reported finding bacteria in reservoir fluids from depths ranging from a few hundred to several thousand feet. While there is some question as to whether these bacteria are contaminants or species indigenous to the formation where found, evidence is being accumulated, strongly suggesting that bacteria live in certain petroliferous formations. For example, Müller (1944) found bacteria in 13 out of 38 aseptically collected side-hole samples from oil sands and oil-bearing limestones. Similarly we have found bacteria in part of the cores collected from oil or sulfur wells, with all possible precautions being taken to exclude contamination.

Finding no bacteria in certain samples proves that reservoir fluids and oil-well cores can be collected without contamination, there being no reason to suspect the presence of indigenous microflora in all formations. If bacteria are alive and active, most likely they will be found only in formations containing sufficient water, minerals, available carbon, and energy source. Moreover, other environmental conditions such as pressure, temperature, pH, E_h, lack of toxics, etc., must be conducive to the multiplication and metabolism of microorganisms. Even when present it is often extremely difficult to detect bacteria in certain sediments, since they may require long periods of incubation and special conditions for growth. It is amazing that some bacteria seem to withstand the shock of being transplanted abruptly from environments where extremes of temperature, hydrostatic pressure, salinity, redox potential, etc., prevail, to laboratory conditions.

Finding in petroliferous sediments almost exclusively anaerobic sulfate-reducing bacteria, and rarely any aerobes that predominate in surface soil and water, is highly significant, though not conclusive evidence, for their indigenous origin. Some of these have been shown to be able to grow in oil-well brines enriched with crude oil (ZoBell, 1950) or molecular hydrogen (ZoBell, 1947) as the sole source of energy. Also suggestive of the indigenous nature of certain bacteria isolated from oil wells is the observation that they grow best or exclusively at temperatures, pressures, and salinities characteristic of the formation. Recently we have worked with sulfate-reducing bacteria from depths of 9,000 feet which were most active at around 5,000 psi, whereas most bacteria isolated from near surface material are inhibited or killed when subjected to such hydrostatic pressures (ZoBell and Johnson, 1949).

That bacteria may be active in petroliferous sediments is indicated by the frequent decreased sulfate and increased sulfide content of brines associated with crude oil. While inorganic reactions might account for the reduction of sulfate, it has been established that bacteria could be responsible for this change (Ginter, 1934, ZoBell and Rittenberg 1948). Likewise, the common absence of hydrogen in oil fields, where one might expect it as a by-product of radioactivity (Honig and Sheppard, 1946), bacterial fermentations (ZoBell, 1947), or certain chemical reactions (Nichols, 1941), may be attributable to the action of bacteria in sediments which utilize this gas. Observed changes with depth or age, in the amount and properties of organic matter in long cores of recent sediments, are believed to be attributable to bacterial activity, because in vitro tests under simulated conditions similar changes have been produced.

While only a few specialized bacterial species have been detected in older sediments, there occur in recent sediments a large variety of microorganisms capable of attacking all kinds of organic compounds as well as capable of catalyzing numerous inorganic reactions. In recent sediments both anaerobes and aerobes exist, the latter predominating in surface materials. The number and variety of chemical reactions known to be catalyzed by bacteria far exceed those attributable to all plants and animals together (Stephenson, 1947) Bacteria owe their biochemical versatility to the vast array of enzymes (biocatalysts) which they produce. There are varieties that thrive throughout the entire range of environmental conditions encompassed by the "geological fence" for the origin of oil (Cox, 1946), and, in the presence of food and energy, they may multiply with amazing rapidity.

MODIFICATION OF ORGANIC MATTER

Except in preservative environments, the organic remains of plants and animals start to undergo microbial modification shortly after the death of the organisms. In the presence of free oxygen much of the organic material may be oxidized or mineralized by microorganisms with carbon dioxide, ammonia, water, and sulfate being produced. In this process from 30 to 40 per cent of the organic carbon may be converted into bacterial cell substance. Part of the latter may be quite complex, and together with complex organic substances of plants and animals that are also relatively resistant to microbial decomposition, go to make up marine humus. The humus content of marine sediments will be highest in environments where organic production is large, the rate of sedimentation is fast, and where conditions are anaerobic. It is in such environments that protopetroleum is believed to be deposited.

As elaborated by Waksman (1933, 1935, 1936), humus is an accumulation of substances of plant, animal, and bacterial origin, that is fairly but not absolutely resistant to microbial decomposition. It has a higher carbon content than the plant, animal, or bacterial substances from which it originated, usually 52 to 58 per cent, and a lower nitrogen content.

When buried in sediments, under favorable conditions marine humus may be slowly modified by a combination of microbial, chemical, physical, and geological factors, with the formation of crude oil by processes that are not well understood. In the complete absence of atmospheric oxygen, anaerobic bacteria slowly attack marine humus with the formation of substances which contain relatively less oxygen, nitrogen, sulfur, and phosphorus, leaving residual material relatively richer in carbon and hydrogen and consequently more like petroleum which consists largely of carbon and hydrogen. This may be illustrated by the following proximate analyses summarized in table 1.

TABLE 1

	Marine organisms	Marine humus	Crude oils
	Per cent	Per cent	Per cent
Carbon	45–52	52–58	82–87
Hydrogen	5–9	6–10	11–14
Oxygen	25–30	12–20	0.1–5
Nitrogen	9–15	0.8–3	0.1–1.5

The pathways by which marine humus is converted into crude oil are still obscure, but there can be no doubt that bacterial processes are largely responsible for the formation of humus. Associated with the humus in recent marine sediments are traces of liquid and solid hydrocarbons which probably come in part from decomposing plants and in part from bacterial bodies. While quantitatively the amount of hydrocarbons produced by plants (Hackford, 1932; Seyer, 1933; Chibnall, *et al.*, 1934; Sanders, 1937) may be sufficient to account for all known petroleum deposits, the author is aware of no geological evidence to explain the selective migration and accumulation of petroleum hydrocarbons exclusively from this source. Possibly such preformed hydrocarbons contribute somewhat, but the main bulk of petroleum is probably produced at some depth in older sediments as attested by the lack of evidence that any petroleum has been formed since the Pliocene (Cox, 1946).[2]

[2] Since this was written, Paul Smith (1952)

The recent observations of Whitehead and Breger (1950) on the low temperature pyrolysis of organic extract from marine sediments suggest that certain humus might be quite readily converted into petroleum hydrocarbons. Contributing mechanisms may be contact catalysis, radioactivity (Lind, 1938), bacterial activity, and other processes at temperatures prevailing within the limits of the "geological fence."

Studies on the decarboxylation of organic compounds, deamination reactions, transmethylations, and hydrogen sulfide liberation, suggest various mechanisms by which anaerobic bacteria can convert marine humus into substances more akin to petroleum. Further observations on such bacterial reactions are urgently needed to elucidate the problem of the origin of oil.

BACTERIA PRODUCE HYDROCARBONS

The anaerobic fermentation of organic matter nearly always results in the formation of methane, a common constituent of natural gas and crude oil. Methane is also formed by the reduction of carbon dioxide with either organic compounds or molecular hydrogen serving as a source of energy (Barker, 1936; ZoBell, 1947). The bacterial production of ethane has been reported (Neave and Buswell, 1938; Rawn *et al.*, 1939), and there is somewhat less conclusive evidence for the microbial formation of propane, butane, ethylene, and other gaseous hydrocarbons in small amounts.

A good many bacterial species (Porter, 1946) produce carotene, flavorhodin, and other complex pigmented hydrocarbons having the empirical formula $C_{40}H_{54-58}$, which may be susceptible to hydrogenation. It is especially significant that some of these pigmented hydrocarbons produced by bacteria possess the benzene nucleus. Phenol, cresol, and possibly other aromatic compounds commonly found in crude oil are produced by marine bacteria from the degradation of proteins (Updegraff, 1948).

Ether-soluble unsaponifiable oily extracts produced from fatty acids by sulfate-reducing bacteria were identified by elementary analysis and physical properties as a mixture of hydrocarbons ranging from C_{10} to C_{25} (Jankowski and ZoBell 1944). An optically active mixture of liquid and solid hydrocarbons was extracted from marine bacteria by API Research Project 43B workers (Whitmore, 1945). Similar observations lead the author to believe that all anaerobic bacteria produce as part of their cell substance, traces of liquid and solid hydrocarbons. Although the amount of such hydrocarbons is small, if they are more resistant to decomposition than the rest of the bacterial cell substance, hydrocarbons may gradually accumulate as the organic material is used over and over again by bacteria.

According to Bach and Sierp (1924), the anaerobic degradation of fats under natural conditions resulted in the formation of liquid hydrocarbons. An increase in the hydrocarbon content of diatoms undergoing degradation by anaerobic bacteria was observed by Clarke and Mazur (1941), one of the principal hydrocarbons produced being hentriacontane, $C_{31}H_{64}$.

HYDROGEN UTILIZATION

Bacteria which utilize molecular hydrogen may contribute to oleogenesis and also help to account for the paucity of this gas in oil fields. Free hydrogen is commonly formed during the fermentation of organic matter (ZoBell, 1947) and it may be produced by radioactivity (Lind, 1938), or by a variety of chemical reactions.

In reviewing the literature on this subject, ZoBell (1947) has pointed out

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has reported extracting from recent marine sediments appreciable quantities of paraffinic, naphthenic, and aromatic hydrocarbons, the amount of which increased with depth throughout the length of a 103-foot core from the Gulf of Mexico. The extrapolation of his data indicated that a cubic mile of such sediment might contain 13,000,000 barrels of this extract resembling crude oil.

that several species of anaerobic bacteria found in marine sediments catalyze the oxidation of hydrogen. Some bacteria activate the hydrogenation of unsaturated compounds:

$$RHC=CHR+H_2 \rightarrow RCH_2CH_2R$$

where R is an alkyl group or other organic radical. Other bacteria catalyze the reductive deamination of amino acids with molecular hydrogen:

$$RCHNH_2COOH+H_2 \rightarrow RCH_2COOH+NH_3$$

Of special interest are anaerobic bacteria which reduce carbon dioxide to methane:

$$CO_2+4H_2 \rightarrow CH_4+2H_2O$$

this being an exothermic reaction yielding sufficient energy to provide for the synthesis of bacterial cells which catalyze the reaction. This may also be said of autotrophic sulfate-reducing bacteria which obtain their energy for growth from the oxidation of hydrogen:

$$H_2SO_4+4H_2 \rightarrow H_2S+4H_2O$$

Finding such bacteria in oil fields may help to account for the decrease in the sulfate content and increase in the sulfide content of brines characteristic of oil fields. Such bacteria may also contribute to oleogenesis because they have been shown to produce appreciable amounts of ether-soluble unsaponifiable material. We have found enough of these organisms in petroliferous sediments to account for the formation of 6.2×10^{-10} mgm of oily material per cc of sediment per year. Although the oily material is believed to consist largely of hydrocarbons, conclusive proof is still lacking. The carbon necessary for this synthesis comes from carbon dioxide or carbonates:

$$CO_2+3H_2 \rightarrow (-CH_2-)+2H_2O$$

where $(-CH_2-)$ represents a building block of bacterial cell substance, part of which may be hydrocarbon (Sisler and ZoBell, 1951).

BACTERIAL MODIFICATION OF CRUDE OIL

Virtually all kinds and classes of petroleum hydrocarbons have been shown to be susceptible to bacterial oxidation under favorable conditions (ZoBell, 1946b; 1950a). Several dozen samples of crude oil from representative fields have also been found to be attacked by bacteria. Unfortunately, very little is known regarding the changes caused by bacteria, but it is axiomatic that those crude oils which support the growth of bacteria may be modified.

Certain constituents of crude oil may be selectively decomposed or converted into other substances. Tausson and Aleshina (1932) believe that certain sulfate-reducing bacteria tend to convert paraffinic hydrocarbons higher than C_{10} into naphthenic hydrocarbons. The preferential attack of sulfur compounds and other changes in the properties of a variety of Russian crudes caused by sulfate-reducing bacteria has been reported by Maliyantz (1935). We have observed both increases and decreases in the gravity of crude oils under the influence of bacteria, the direction and magnitude of the reaction appearing to depend upon the type of bacteria present and environmental conditions.

Tausz (1919) found an increase in the asphaltic residue of Mendoza crude oil from an initial content of 0.3 per cent to 5.2 per cent as a result of bacterial activity. Bacterial activity was found by Tausson and Shapiro (1934) to affect the index of refraction, iodine number, saponification number, density, and physical appearance of Emba crude oil samples. The middle fractions and unsaturated compounds were selectively attacked in laboratory experiments.

There are several mechanisms by which bacteria attacking oil at the oil-water interface bring about the formation of water emulsions of oil. Possibly such bacterially produced water emulsions may help to account for the migration of oil. Water emulsions are caused partly by fatty and naphthenic acids produced by bacteria from petroleum hydrocarbons, which suggests that such acids not infrequently found in oil fields may be the result of bacterial activity.

Given sufficient time and favorable conditions, bacteria can be expected to bring about the quantitative destruction of petroleum hydrocarbons in an aerobic environment. This may help to account for the absence of oil from many environments and its disappearance from sediment samples stored in the presence of free oxygen. In anaerobic environments characteristic of petroliferous sediments, crude oil constituents may be slowly and selectively attacked at the oil-water interface. Certain heavy metals, low redox potentials (ZoBell, 1946a), high concentrations of hydrogen sulfide, and other unfavorable conditions may retard or prevent bacterial activity. In a closed system the toxic metabolic products of bacteria themselves may limit bacterial activity.

In a closed system such as a petroleum deposit, anaerobic bacteria might conceivably attack hydrocarbons at the oil-water interface. However, the extent of their activity would be limited by toxic metabolic products and competition for essential nutrients. Consequently, the few surviving bacteria would soon reach a condition of dynamic equilibrium in which multiplication or reproduction would be limited by the rate of diffusion of toxic products away from, and essential nutrients into, the biosphere. This condition of dynamic equilibrium, in which bacterial activity is envisioned as being extremely slow, may be altered by diastrophism, drainage from an oil well, or by any disturbance that may promote the movement of oilfield fluids.

LIBERATION AND MIGRATION OF OIL

Bacteria growing in marine sediments may contribute to the liberation of oil from oil-bearing materials and promote its flow in various ways. Most obvious is the bacterial decomposition of the organic matrix of plant bodies bearing oil, thereby freeing oil droplets to coalesce with other oil droplets.

A second mechanism by which bacteria dissolve carbonate or sulfate rocks on which oil is adsorbed has been described by ZoBell (1947). The dissolution of such sedimentary materials may not only release adherent oil, but it may also favor the flow and accumulation of oil by the formation of void spaces and channels.

Third, bacterially produced carbon dioxide tends to decrease the viscosity of oil, particularly when under pressure. This may favor the flow of oil. Bacterially produced methane may dissolve oil or decrease its viscosity to a point where it flows more readily. When methane, hydrogen, and other gases are produced by bacteria in microtraps (ZoBell, 1950b) entrapped oil may be expelled.

Fourth, the tendency of certain bacteria to grow on solid surfaces is another mechanism by which adherent oil may be removed from the surface of sedimentary particles. Those that produce detergents are most effective. Bacterially produced detergents and fatty acids both bring about water emulsions of oil that may promote its flow to a structural or stratigraphic trap.

Regardless of the problematical practical applications of the bacterial process to the secondary recovery of oil, bacteria that induce the release and flow of oil are believed to have played an important part in the migration and accumulation of oil throughout the geological ages.

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Bacterial Life at the Bottom of the Philippine Trench[1]

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BACTERIA IN ABUNDANCE have been found (*1*) in virtually all samples of marine bottom deposits, examined regardless of the depth of the overlying water. Until recently, ever, very few samples had been taken from ths exceeding 2000 meters, and none from little e than half the depth of the most abyssal oceanic p. Certes (*2*) reported the presence of bacteria in tom deposits collected on the *Talisman* Expedition n depths as great as 5100 meters. Significantly, tes (*3*) observed that the organisms from around 0 meters were able to tolerate hydrostatic pressure roximately isobaric with this depth; namely, 500 ospheres. On the Humboldt Plankton Expedition the West Indies, Fischer (*4*) found bacteria in ral deep-sea sediment samples, 5280 meters being greatest depth that he explored. Marine micro- ogists at the Scripps Institution recovered bacteria n mid-Pacific mud at a depth of 5300 meters t. 14° 22′ N, Long. 133° 06′ W) and in a sample bottom deposits collected off the coast of Bermuda n the floor of the Atlantic Ocean at a depth of 0 meters.

ecently the Danish *Galathea* 'Round the World p Sea Expedition has afforded facilities for the ection and microbiological analysis of sediment ples from the deepest known parts of the oceans. ny samples were taken from depths exceeding 6000 ers, including several from the Philippine Trench epths greater than 10,000 meters. Confirming and her delineating the observations of the U.S.S. *e Johnson* (*5*), this trench was shown by echo th recorder to extend for about 100 miles from 4′ N × 127° 05′ E to 10° 41′ N × 127° 37′ E on a about 20° west of north. For most of its length walls rise precipitously from the bottom, which ly from one-half mile to three miles wide. Only he best of navigation was it possible to delineate the trench and to stay on station from 8 to 18 hours, the time required to collect a sample from the bottom. Often this was achieved in the face of adverse meteorological conditions characteristic of the monsoon and typhoon season in Philippine waters during July and August 1951.

Samples of bottom deposits were collected by means of a plastic-lined Kullenberg corer and a Petersen grab. Immediately after they were brought to the surface, radially central samples were removed with sterile instruments to secure uncontaminated material for microbiological analysis. The direct microscopic method and several standard cultural procedures were employed to demonstrate the presence of bacteria. Duplicate cultures were incubated in the ship's refrigerator at 2.5° C, which approximates the sea floor temperature, and at air temperature, which varied little from 30° C. Part of the cultures were incubated at atmospheric pressure and part in steel cylinders (*6*) at approximately the pressure of the environment from which the inocula were collected. Representative findings for five samples from the Philippine Trench are summarized in Table 1. For comparison the results from two samples taken from lesser depths on either side of the trench are presented. Sea water enriched with peptone, beef extract, and yeast extract was employed as the culture medium.

Table 1 shows the number of bacteria demonstrated in the topmost layer of bottom sediments by the minimum dilution method. The abundance of bacteria was found to decrease sharply with depth below the mud-water interface. Only 10 to 100 viable cells could be detected per gram of mud from depths 75 to 100 cm below the surface of the sea floor. All cultural counts must be regarded as minimal, however, because no one medium or set of cultural conditions could conceivably provide for the reproduction of all bacteria.

The presence of large numbers of bacteria in bottom deposits was confirmed by the direct microscopic observation of freshly collected samples. Direct microscopic counts, however, had little quantitative significance, owing to the difficulty of distinguishing particles of sediment from bacteria, and other practical difficulties caused by vibration and other movements of the ship at sea.

The largest cultural counts were obtained in nutrient medium incubated at around 2.5° C. It is also

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TABLE 1

NUMBER OF BACTERIA PER GRAM WET WEIGHT OF BOTTOM DEPOSITS DEMONSTRATED BY THE MINIMUM DILUTION METHOD

Station No.	Location of station		Water depth (meters)	Incubated at *ca* 30° C		Incubated at *ca* 2.5° C	
	Latitude	Longitude		1 atm	1000 atm	1 atm	1000 atm
413	10° 20′ N	126° 36′ E	10,387	10^2	10^3	10^4	10^5
418	10° 13′ N	126° 43′ E	10,462	10^2	10^3	10^3	10^6
419	10° 19′ N	126° 39′ E	10,417	10^3	10^3	10^3	10^5
420	10° 24′ N	126° 40′ E	10,418	10^3	10^5	10^4	10^5
421	10° 29′ N	126° 05′ E	1,023	10^4	0	10^5	0
422	10° 49′ N	126° 01′ E	2,010	10^4	0	10^6	0
424	10° 28′ N	126° 39′ E	10,395	10^3	10^4	10^4	10^6

noteworthy that from ten to a hundred times more bacteria from the bottom of the Philippine Trench developed at 1000 atmospheres than at atmospheric pressure. Such observations establish the occurrence of barophilic bacteria at the greatest known oceanic depths, but much more work will be required to explain the temperature-pressure relationships of the organisms.

The time required (4 to 10 hours) to haul the samples from the deep-sea floor to the surface may account for finding in the mud no abnormally elongated bacterial cells such as those observed by ZoBell and Oppenheimer (*6*) in cultures incubated at 600 atmosphere. Predominant were rod-shaped bacteria ranging in length from 2 to 4 μ. Many were capsulated. Endospores were found in most mud samples. Pairs of rods were common, and some occurred in short chains. Species of *Pseudomonas, Flavobacterium, Vibrio, Spirillum, Bacterium, Micrococcus, Bacillus,* and *Clostridium* were identified, and probably other genera were present. The identification of species poses special problems because of the unique pressure and temperature requirements of the deep-sea bacteria.

It may be more remarkable that many bacteria from abyssal depths survived at 1 atmosphere and 30° C than that most deep-sea bacteria seemed to prefer the low temperature and high pressure characteristic of what appears to be their natural habitat. Perfected sampling techniques will be required to determine to what extent deep-sea bacteria may be injured by the sudden changes in pressure and temperature incidental to their transfer from the sea floor to the surface. Finding some survivors fails to prove that many others may not have succumbed to the sudden change of climate. None of the animals recovered from the bottom of the Philippine Trench reached the surface alive. As reported by Bruun (*7*), the bottom fauna included actinians, amphipods, bivalves, echiurid worms, holothurians, and tanaids. The author concurs with Bruun in believing that deep-sea bacteria as well as animals are affected more by the change in temperature than by the change in pressure, althoug
the two effects are closely related. As indicated by th
observations of ZoBell and Johnson (*8*), who applie
the term "barophilic" to bacteria having a preferenc
for high hydrostatic pressure, the temperature toler
ance of bacteria is affected by the pressure.

Barophilic bacteria in abundance have also bee
demonstrated in several other abysses at depths rang
ing from 7200 to 10,080 meters, including the Soend
Deep in the Indian Ocean, the Weber Deep in th
Banda Sea (*9*), and the Kermadec Deep in the sout
Pacific Ocean (*10*). Besides functioning as geochem
ical agents the deep-sea bacteria are believed to serv
as an important source of food for bottom-dwellin
animals, whose only other source of nutrient is th
sparse supply of organic substances reaching the
from the photosynthetic zone. The bacteria, which ar
known to nourish many animal species, can obtai
their energy for growth from waste or dissolve
organic matter in the circulating sea water or, in th
case of certain autotrophic bacteria, from the oxida
tion of ammonium, methane, hydrogen, and possibl
other inorganic substances.

Besides establishing the existence of bacterial lif
on the sea floor at depths exceeding 10,000 meters, th
greatest depth being 10,462 meters, the project ha
provided barophilic cultures for further investigation
of pressure as a physiological factor.

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BREEDING HABITS OF *HYPERPROSOPON ARGENTEUM*, A VIVIPAROUS FISH OF CALIFORNIA[1].—Although the live-bearing seaperches and surfperches of the family Embiotocidae are common along most of the west coast of North America and constitute one of the outstanding elements in the local fauna, little has been published regarding their breeding habits. Eigenmann (1894, Bull. U. S. Fish Comm., 12 (1892): 381–478) stated hat *Cymatogaster aggregata* becomes gravid about he first of December, after a six-month period of perm storage. He further stated that the act of opulation had never been observed for any embiotoid. Hubbs (1917, Copeia, 39: 73-74) described the opulation of *Cymatogaster aggregata*, which he oberved on July 5, 1916. The female of the mating air was giving birth to its last young. Two other mall species, comprising the genus *Micrometrus* including *Amphigonopterus*) agree with *Cymatoaster* in the lapse of one year between copulation nd gestation (Hubbs, 1921, Biol. Bull., 40: 189-91).

On November 3, 1950, our first definite observaions on the breeding habits of *Hyperprosopon rgenteum* Gibbons were made underwater with the id of a self-contained diving apparatus. Mating as taking place in a recess along the rocky shorene of La Jolla, California. It was then determined hat the species was mating in other similar areas long the coast, not only near La Jolla but also bout the breakwaters near Newport. Similar acvities were noted during diving operations at Pt. rguello on October 23, 1949, but were not recogzed then as involving copulation.

Many individuals were observed in water 4 to 2 feet deep, from 25 to 200 feet offshore, over rocky eas that were interspersed with sand patches. The ther dense bottom plant growth consisted of *hyllospadix*, *Egregia* and coralline algae.

Ordinarily this species aggregates in more or less nse schools varying in numbers up to several hundred or even thousand. Little tendency to disperse into small groups was noted during the nonbreeding season. While breeding, however, many pairs were found isolated and no large schools were encountered. Schools of 4 to 10 females accompanied by one male were carefully observed. When such a school was frightened, the females would lead off and the male would remain behind as though maintaining a rear guard, warding off intruders, such as other males. At times he allowed the school of females to move completely away. No mating activities were noted in such groups.

Females were much more inquisitive about the diver than the male and frequently came within a few feet of the diver's "blind" behind some seaweed. The courting male, paying no heed to the diver's presence, paraded continuously back and forth in front of the female.

Many paired fish 140 to 170 mm. in total length were observed actively swimming and engaging in breeding activities 2 to 5 feet above the bottom. The male, usually of the same size as the female, remained beside her, unerringly matching her darts and turns. Usually he stayed slightly below the level of her dorsal fin and kept his snout even with her pelvic fins. He frequently passed under the female, brushing her abdomen with his dorsal fin. If the female stopped the male promptly took a position in front of her and swam back and forth, with his snout tilted upward and his fins spread, never more than a body length away.

During actual copulation the genital openings were closely apposed, while the fish were actively swimming as well as when quiet. From time to time the bodies were tilted laterally so as to bring the anal regions still closer together. It is assumed that the spermatozoa are transferred to the oviduct at this stage of mating behavior.

The encroachment of another male was immediately met by a quick charge of the courting male toward the snout of the intruder. Unless the

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intruder was larger, the courting male was usually not replaced. The males made no attempt to drive away closely related species in the area, such as *Phanerodon furcatus*, *Damalichthys vacca*, *Embiotoca* sp. and *Micrometrus minimus*. A male did not invariably remain with a single female. He often wandered to another, usually unaccompanied female, making his approach conspicuous by tilting his snout upward and then spreading his fins.

In this species the sexes are usually distinguishable in life and the differentiation becomes more trenchant during the breeding season. The anal fin of the male is conspicuously angulated where one ray is modified to form a very strong triangular bony plate. The corresponding ray of the female is little modified. The fins of the male, particularly the pelvics, are lemon yellow and the scales near the pectorals show yellow spots. Series of pigment spots on the body scales form 5 or 6 usually complete vertical bars. The fins of the females are not as pronouncedly colored, but the dark barring of the body is very distinct. During the non-breeding season the bars are faint.

Two males taken from the breeding groups on November 3 were definitely ripe, but a careful examination of a female, by Teh Ping Lin, a fellow graduate student familiar with cytology and chromosome analysis, revealed no ova.

Young taken from a female on January 15, 1951, had a mean standard length of 16.5 mm. Birth of the young began in the ocean about the middle of April, as was also true of some other species of the family (*Brachyistius frenatus*, *Damalichthys vacca* and *Embiotoca* sp.). Specimens born in the aquarium on April 17 to 23, 1951, had a mean standard length of 40 mm. They showed no indication of the natal maturity characteristic of three small species of the family (Hubbs, 1921: 187-89).

The gestation period of *Hyperprosopon* thus appears to approximate 5 to 6 months. In this species the sperm is apparently not stored for any long period. The number of young, commonly 5 to 12, varies with the age of the parent.—ANDREAS B. RECHNITZER AND CONRAD LIMBAUGH, *Scripps Institution of Oceanography, University of California, La Jolla, California.*

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IRON ASSIMILATION BY MARINE DIATOMS[1]

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The relationship of marine productivity to the availability of iron has been discussed by Gran (1933), who suggested that organically combined iron introduced into coastal waters from terrestrial run-off is responsible for phytoplankton abundances. He substantiated his argument by demonstrating that the growth of the neritic diatom *Skeletonema costatum* was stimulated by soil extract containing 0.2 micromole of iron per liter, although the iron bound into oxyhemoglobin molecules had no effect. Hopkins (1930) has indicated that ionic iron is necessary for the growth of *Chlorella,* and Rodhe (1948) defines the available iron for utilization in culture by fresh water algae as that which has been stabilized by combination with citrate.

Harvey (1937a) has demonstrated that diatoms are able to assimilate ferric hydroxide or ferric phosphate in colloidal or particulate form and to utilize it in their growth. He has further shown, using the calculated saturation concentrations of ferric and ferrous ions in marine waters, that diatoms accumulate 10,000 times more iron than could possibly be obtained from diffusion of iron ions from the environmental waters. His treatment considered a stationary spherical living cell with respect to the environment, whereas a falling diatom would encounter and take up somewhat more iron.

Continuing an investigation of the minimal quantities of mineral nutrients needed for optimal growth of the marine diatom *Asterionella japonica* (Goldberg, Walker and Whisenand, 1951), an assessment of iron uptake presents the following questions. What is the minimal content of iron per cell needed for further division? What constitutes available iron? Finally, inasmuch as the concentration of iron in marine waters has been found to be highly variable (Cooper, 1948), can iron content be one of many possible parameters in the nutrient index of the productivity equation of Riley, Stommel and Bumpus (1949)?

CULTURE TECHNIQUES

The culture techniques used in the following experiments, unless otherwise indicated, have been described previously in the work on phosphate uptake (Goldberg, Walker and Whisenand, 1951). To maintain symmetry with respect to these investigations the same culture of *Asterionella japonica,* which was isolated from the plankton samples in the winter of 1950, was used. The initial phosphate level was adjusted to 2.5 to 3.0 micromoles of phosphate per liter.

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[1] Contribution of the Scripps Institution of Oceanography, New Series No. 572.

IRON ASSAY

The iron determinations were made either by the colorimetric method of Buch (1942) or through the use of radioactive iron. In the former procedure the extinction of the alpha-alpha′ bipyridyl complex of iron was measured at 522 mμ in 100 mm. cells in a Beckman Model DU Spectrophotometer. The method determines both ferric and ferrous iron, but only a portion of the organically bound or particulate iron.

Iron [2] containing the radioactive isotopes Fe^{55}, which decays by K capture, and Fe^{59}, a beta and gamma emitter, was employed as a tracer for this element. The radio iron was plated from aliquots of sea water samples onto 10 $cm.^2$ copper planchets following the procedure of Ross and Chapin (1942). As assayed under an end-window Geiger-Muller tube with a window thickness of 1.8 $mg./cm.^2$, the specific activity was 2500 counts per minute per micromole.

IRON PARTITION IN CULTURE BOTTLES

In the first experiments with radioactive iron it was found that 80 to 90 per cent of the iron added initially as the ferric citrate complex was adsorbed within one day to the walls of the culture bottle. To eliminate this adsorption, the culture bottles were coated with "Desicote," a polymer of silicon (manufactured by Beckman Instruments, Inc., South Pasadena, California). The coated bottles had no adverse effect upon diatom growth, as was evident from control runs in both treated and untreated bottles. The bottles retained their coating for periods up to one month. At the end of an experiment the bottles were washed with a detergent and thoroughly rinsed with distilled water.

Radioactive ferric citrate, freshly prepared, was introduced into sea water of pH 8.00 to give an iron concentration of 2.2 micromoles per liter. Aliquots of 10 ml. of the solution were centrifuged for thirty minutes and the supernatant liquid assayed radiometrically for iron. The results are listed in Table I. It is observed that hydrolysis of iron citrate occurs to a considerable extent in a period of four days.

As is noted in the table, the decomposition was noticeably accelerated both by light and by stirring. The light effect is probably similar to that reported by Peltz and Lynn (1938) who found that iron citrate complex was partially decomposed in sunlight to CO_2 and a soluble ferrous ion. The ferrous ion formed in this way can readily be oxidized to give the ferric hydroxide. The more pronounced effect of stirring upon the hydrolysis is undoubtedly due to the formation of large particulate masses by collisions of smaller iron hydroxide particles, and to more rapid oxidation of any ferrous ion formed.

As pointed out by Harvey (1945), iron ascorbate has less tendency to become hydrolyzed in saline media, if the solution is freshly prepared. On standing, stock solutions of iron ascorbate, originally tinted but a very light green, assume deep brown colorations. It was found that ferric ascorbate was not decomposed for periods up to one week, but after longer periods the formation of centrifugable iron hydroxide followed the course of iron citrate solutions. Iodoform tests on both the

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[2] The radioactive iron metal used in this investigation was supplied by the Oak Ridge National Laboratory on allocation from the Isotopes Division, U. S. Atomic Energy Commission.

TABLE I

The hydrolysis of iron complexes in sea water solutions

Complex of ferric ion	Time elapsed since addition of iron complex (days)	% of original iron remaining in supernate	Remarks
Citrate	0	100	Light, stirred
	1	64	
	2	29	
	3	20	
	4	11	
	6	6	
Citrate	4	50	Dark, unstirred
	4	10	Light, stirred
	4	31	Light, unstirred
Ethylene diamine tetra-acetate	0	100	Light, stirred
	1	88	
	3	80	
	6	15	

ferric citrate and ferric ascorbate solutions were positive within two weeks after preparation.

Ethylenediamine tetra-acetic acid chelates with trivalent iron and this complex was studied as a potential iron source. However, after six days 85 per cent of the iron had hydrolyzed at a pH of 8.25. These results are consistent with the experiments of Jacobson (1951) who found instability of the complex in basic aqueous solutions.

It should be noted that in all cases involving the complexing of iron, the iron and complexing agent were mixed in a 1 : 2 molar proportion. The iron concentration was 2.2 micromoles/liter.

UPTAKE OF IRON BY ASTERIONELLA JAPONICA

In order to establish a minimal cell content of iron necessary for further growth, varying amounts of iron in the form of iron citrate were added to the culture bottles with an initial diatom inoculum of 300–400 cells/ml. The culture medium was assayed for iron colorimetrically before the addition of iron citrate. If the nutrient water showed no iron content, it was used in the growth experiments. It was normally found that inshore surface sea water filtered through a Whatman No. 42 paper was free of iron within the limit of the analytical method (0.1 micromole per liter).

The results of a typical experiment are given in Table II. No growth was observed until the initial iron concentration exceeded 0.8 micromole per liter. Both growth and final population of the cells could be controlled by the initial iron concentration. The iron per diatom, when leveling-off of the exponential growth occurred, averaged 1.0×10^{-7} micromoles per cell. We have assumed that essentially all the iron was removed by the biomass. Since the maximum cell densities were not reached until 6 or 8 days after inoculation, the greater part of the iron available to the diatoms was in particulate form.

TABLE II

Iron uptake by Asterionella japonica

Culture bottle	1	2	3	4	5	6
Initial iron in micromoles/liter	0.8	1.6	2.2	2.5	3.4	3.4
Final diatom population cells/ml.	0	14,700	21,700	18,200	41,900	41,100
Final iron content of diatoms micromoles/cell × 10^7	0	1.1	1.0	1.4	0.81	0.82

Initial diatom inoculum: 300 cells/ml.
Initial phosphate: 2.62 micromoles/liter.

Humic acid has been reported as a complexing agent which makes iron more readily available to various plants and micro-organisms. Harvey (1937b) found increased growth with an artificial iron humate, but the effect was less than that of the iron citrate complex. Although the chemical formulae for the various iron complexes that are present in both natural and synthetic preparations are undetermined, it was desirable to ascertain whether iron humate might be a suitable nutrient source for *Asterionella japonica.* The synthetic humic acid and iron humate solutions were prepared according to the method of Burk, Lineweaver and Horner (1932). The iron content of the iron humate solutions was determined colorimetrically after a wet digestion with 3 : 1 nitric : perchloric acid mixture. The iron humate does not give centrifugable products from sea water solutions when prepared in this fashion.

The results of the humate experiments are given in Table III. Iron citrate was added to control cultures. The initial phosphate level was 2.7 micromoles per liter and the diatom inoculum was 750 cells/ml. Humate as the source of iron did not promote growth. However, the excess humic acid constituents did not deter diatom growth, as is seen in the results of bottle 5. We may therefore conclude that this form of iron humate is not available for metabolic utilization by *Asterionella japonica.*

Freshly prepared radioactive iron ascorbate was added to the culture bottles to give an initial concentration of 1.45 micromoles per liter. Three moles of ascorbate were present for each mole of iron. Exponential diatom growth was observed up to 30,000 cells per ml.; however, the cells appeared misshapen and unhealthy. No detectable iron was removed from the solution by radioactive assay of

TABLE III

Diatom growth experiments with ferric humate as the source of iron

Culture flask	1	2	3	4	5	6
Iron form	Humate	Citrate	Humate	Citrate	Citrate + Humic acid	Humate
Initial iron concentration micromoles/liter	12.5	14	12.5	14	14	6.3
Final concentration diatoms cells/ml.	0	81,000	0	62,000	70,000	0

the supernatant solution. To confirm this finding the diatoms were filtered, digested in the 3:1 nitric: perchloric acid mixture and the iron activity was determined radiometrically. The cell content of the accumulated radio-iron averaged 1.9×10^{-9} micromoles per cell. This is about 2% of the minimal iron content as determined from the uptake experiments previously described. The initial amount of particulate iron in the culture flasks was 1.8 micromoles per liter added as ferric chloride solution.

One final experiment was undertaken to confirm the observation that in the absence of complexed ferric iron and in the presence of particulate iron, diatom growth could proceed. Cells from a growing sub-culture were placed in a dialyzing sac which held 50 ml. of nutrient solution such that there was an initial diatom population of 800 cells/ml. The sac was held in place by a rubber stopper in a 250 ml. volumetric cylinder which contained 210 ml. of solution. Freshly prepared iron citrate was introduced into either the dialyzing sac or the cylinder to give an iron concentration of 2.2 micromoles per liter. In the former case the ionic complexed iron penetrated the membrane to give a concentration of 0.01 micromole per liter after 2 days, *i.e.*, 20% of the iron diffused into the outer cylinder. Here normal exponential growth occurred, whereas when the diatoms could receive only the complexed iron as in the latter case, no population increases were noted.

DISCUSSION

From the above experiments it is evident that the organic iron complexes used were not available as a growth nutrient to marine diatoms, whereas particulate and/or colloidal forms of iron are utilized in their metabolism.

Cooper (1935) found that the ratios of iron to phosphorus, in plankton samples consisting almost entirely of diatoms, were 4.2 and 4.4 in two separate determinations. From the experiments of phosphate uptake by *Asterionella japonica*, 5×10^{-8} micromoles of phosphate per cell were necessary for division. Combining this with the minimum iron content of 10×10^{-8} micromoles/cell, we calculate for our cultural populations

$$\mathrm{Fe/P} = \frac{55.85 \times 10 \times 10^{-8}}{30.98 \times 5 \times 10^{-8}} = 3.6$$

The striking agreement between these values suggests that this method of study of cultural diatom populations represents a fair simulation of ocean growth.

Cooper (1948) attributes the extreme variability in iron content in the upper layers of marine waters as due to the random distribution of particles of a large size (*i.e.*, 160 μ), as large as some sand grains. It would be of interest to know what size of iron hydroxide particle might be necessary for diatom division. We may assume a density of the particle as 1.1 and an iron content of 50 per cent. Since 1.0×10^{-7} micromoles or 55.85×10^{-13} grams are needed per cell we have, where r is the radius of the particle,

$$55.85 \times 10^{-13} = \tfrac{4}{3}\pi r^3 \times 1.1 \times \tfrac{1}{2} \quad \text{or} \quad r = 2 \times 10^{-4}\ \text{cm.} = 2\mu.$$

From the above relationships it is noted that a particle of 4 μ radius would furnish enough iron for three divisions.

The use of iron content as a parameter in a nutrient index of a productivity equation now presents itself. However, unlike necessary ionic species, the absolute concentration of iron does not reflect its availability. A direct study is needed of the number of particulate iron particles and their size distribution. One possible approach to this problem has already been initiated in this laboratory. Sea water is filtered through a cellulose membrane filter which retains particles of 0.1 μ in diameter. Following the filtration the membrane is washed with distilled water and dried. The membrane is then cleared with polyoxyethylene sorbitan monolaurate which is saturated with potassium thiocyanate and is acidified with 3 drops HCl per 100 ml. The typical red iron thiocyanate color is produced about any iron particle. By the use of this technique, a study of the size distribution of the iron particles in the euphotic zone of Pacific coastal waters will be made.

SUMMARY

1. With the use of radioactive iron it was found that the marine diatom *Asterionella japonica* utilized only particulate and/or colloidal iron as a growth nutrient, whereas ionically complexed ferric ion as the citrate, ascorbate, or artificial humate was not available for uptake.

2. A minimal content of iron per cell needed for further division was established as 10×10^{-8} micromoles per liter. The ratio of the minimal iron to the minimal phosphate agrees substantially with the iron-to-phosphate ratio in natural plankton samples.

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57. TECHNIQUES FOR RECOGNITION OF LIVING FORAMINIFERA*

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57. TECHNIQUES FOR RECOGNITION OF LIVING FORAMINIFERA*

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SUMMARY

1. Quantitative studies of the distribution of living populations are of importance in ecologic studies and paleoecologic interpretations. Living Foraminifera have been recognized by chemical tests for proteins and by selective biologic stains.

2. Chemical color tests for protein which have been used are the BIURET reagent and MILLON's reagent. Millon's reagent can be used only with Foraminifera having arenaceous tests. Chemical color tests are satisfactory but are difficult to use and give temporary coloration.

3. RHUMBLER'S staining technique, using methyl green-eosin, is complex to use and stains inorganic as well as organic materials in sediment samples.

4. Rose Bengal is a selective stain for protoplasm and gives positive results. It is recommended as the most reliable and efficient stain for recognizing living Foraminifera.

INTRODUCTION

Recent intensive work on Foraminifera ecology has emphasized the need for knowledge of living populations. Until recently, little information was available and little work was being done on distribution of living Foraminifera.

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It is desirable at the present state of our knowledge to obtain quantitative information on the relationship between the distribution of living and dead populations. Previous studies have indicated that these populations are comparable in certain areas but substantiating data from other areas are desirable (Phleger, 1951; 1952). Such determinations would test the basic assumption underlying previous ecologic studies, that quantitative counts of Foraminifera in dried samples are accurate representations of living foraminiferal faunas. There is no information on the seasonal variation of living populations. When this information becomes available it will be possible to obtain definite quantitative information on the rate of addition of empty tests to the sediments. These data may be used as possible indicators of rates of production and sedimentation.

The study of living populations will give insight into the problem of living communities versus aggregates of skeletal remains deposited by physical agencies. If we are to study fossil faunas in the light of modern associations, it is necessary to have some knowledge of the relative importance of these two assemblages. Certain fossil associations may be the result of a natural community or may be merely accumulations of skeletal remains deposited far from their source. The interpretation of fossil strata in the light of ecology requires a knowledge of recently productive areas in relation to unproductive areas as determined by living populations and skeletal remains. It is believed that distribution studies of living Foraminifera are important tools in increasing our knowledge of ecologic and paleo-ecologic relationships.

Prior to 1946, there were few sediment samples available and few samples being collected that were suitable for analysis of living Foraminifera. With the advent of new sampling techniques, numerous carefully collected and preserved samples have become available. This store of samples, and those presently being collected, present ample opportunity for comparative studies of living populations. The purposes of the present report are 1) to describe the methods previously used to identify living Foraminifera; 2) to describe a new method using rose Bengal; and 3) to discuss and evaluate the methods in terms of their sensitivity, accuracy, selectivity, and ease of operation.

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DESCRIPTION OF METHODS

The methods which have been used to differentiate living Foraminifera from empty tests are of two general types. One type utilizes the color reactions for protein and the other involves a combination of biological stains. The methods will be treated here separately since each is subject to different qualifications.

Color Reactions For Protein

Two methods have been used which are based on the color reactions between chemical reagents and one or more of the constituent radicals or groups in the complex protein molecule. Each of the processes utilizes the presence of a different group of constituent radicals in the protein molecule and gives different color reactions.

Millon's Reagent. Millon's reagent is prepared as follows: Digest one part (by weight) of mercury with two parts (by weight) of nitric acid (sp. gr. 1.42) and dilute the resulting solution with two volumes of water. The precipitate which forms is allowed to settle out and the supernatant liquid is used (Hawk and Bergeim, 1937, p. 147). The supernatant liquid is a solution of mercuric nitrate in nitric acid containing some nitrous acid. The solution imparts a red color to proteinaceous material in the presence of heat. This reaction was adapted for use on arenaceous Foraminifera in sediment samples by Phleger (1952). "The sediment was washed over a brass sieve having openings of 0.074 mm. The washed material was placed in a Petri dish with additional tap water. . . Several drops of Millon's reagent were added to the solution and the sample was warmed 4 to 6 hours by the heat of a 75-watt incandescent lamp in a desk stand" (op. cit., p. 322). Care should be taken to remove all inorganic salts from the sample before the reagent is added, since, in the presence of such contaminants, the mercury in the reagent will be precipitated and the solution rendered inert. The red color reaction is due to the presence of the hydroxyphenyl group (C_6H_4OH) in the protein molecule.

Biuret Reaction. The Biuret reagents include sodium hydroxide and copper sulphate. The procedure is as follows: To a washed sample in an aqueous solution an equal volume of 10% sodium hydroxide is added. The preparation is mixed thoroughly and a 0.5% solution of copper sulphate is added drop by drop with constant agitation until a blue solution is produced. Care should be taken not to add an excess of copper sulphate, which may cause a blue precipitate of copper hydroxide. In approximately 20 to 30 minutes a blue to pink color is obtained on any proteinaceous material present. The coloration is due to the reaction between the reagents in solution and two or more linked peptide groups (-CONH-). If it is desirable to preserve the specimens for future examination, the sample should be washed free of the reagents, since otherwise the sodium hydroxide will eventually hydrolize the protein and other organic substances which are present in the tests of many species.

A stable Biuret solution may be made as follows: Prepare a 10% solution of potassium hydroxide by dissolving 100 pellets of potassium hydroxide in ¾ liter of distilled water. Dissolve 0.75 grams of copper sulphate in a small amount of water and add slowly with constant agitation to the hydroxide solution. If necessary, cool the hydroxide solution in a water bath before adding the copper sulphate. The resulting solution will be a dark blue and may be kept indefinitely without deterioration. This solution may be added directly to the washed sample with the same coloration of the protein.

It should be emphasized that if either of the above methods is to be employed, the original sample should be carefully washed free of sea water and fixative before addition of the reagents. In both reagents the alkali forms precipitate with magnesium salts and these interfere with the identification of proteinaceous material. It is necessary that samples to be used for the identification of living specimens be preserved in neutralized formaldehyde or alcohol as soon as possible after collection and before washing. Washing of the sample in fresh water before fixation will cause rupture of the protoplasm and consequent disaggregation. The addition of a fixative serves not only to preserve the protoplasm but to coagulate and harden it, thus presenting a concentrated mass of protein for the action of the above reagents.

Biological Stains

In biological stains there is adsorption of the stain particles on the substance being stained; a reaction between reagents and the protein molecules is not involved. As pointed out by Conn (1946, p. 9), biological stains are simply dyes that are adapted for special purposes.

Methyl green-eosin. Only one method is known to the writer in which biological stains previously have been used to differentiate between living and dead Foraminifera in sediment samples. This is the method employed by Rhumbler (1935, p. 145) using an alcohol solution of methyl green and eosin. The solution is prepared as follows: Mix 50 cc. of a 1% aqueous solution of methyl green, 50 cc. of a solution of 0.8 grams of eosin in a 50% solution of alcohol and 50 cc. of absolute alcohol. The solution should be mixed well before using. Regardless of fixative used when the sample was collected, it is first treated with water or a weak alcohol solution (not over 50%). It is then placed in the stain solution for ½ to ¾ hours. Rhumbler reports that the methyl green-eosin solution, which he has shortened to "Methgreosin," differentially stains detrital material, fecal material, and organic material. The fecal and detrital material are stained green and the organic material is stained red. It is presumed that this reference to "organic material" includes only material which was living at the time of collection. He further preserves his material by washing it in alcohol solutions of increasing concentration (70%, 95%, 100%). The material may then be kept permanently by placing it in clove oil or mounting in Canada balsam.

Rose Bengal. The rose Bengal method was developed as a result of this study and is presently being used by the writer in the differentiation of living and dead Foraminifera. An aqueous solution of rose Bengal is prepared by dissolving approximately 1 gram of rose Bengal in 1 liter of distilled water. The concentration of the stain solution is not critical since it only alters the intensity and not the effectiveness of the stain. The procedure being used at present is relatively simple and adds only one operation to the preparation of a sample for examination. The sediment sample is first washed in a specially designed sieve shaped like an elongated tea strainer and made of stainless steel screening that has an average opening of 0.074 mm. This process washes the sample free of sea water, fixative, and the fine silt and clay size sediment particles. The sample in the sieve is immersed in the stain solution for approximately 10 minutes. The sieve containing the sample is then removed from the stain solution, is rewashed to remove excess stain, and is transferred from the sieve to a counting tray. Rose Bengal imparts a deep rose color to the foraminiferal protoplasm. The specifications of the stain are as follows: Rose Bengal, C. I. 779; $C_{20}H_2O_5T_4Cl_4Na_2$; solubility in water, 36.25%; solubility in alcohol, 7.53%. Rose Bengal has been used in the past primarily in staining bacteria, and as a cytoplasmic stain (Conn, 1946, p. 165-166).

DISCUSSION

The only completely accurate method of determining the true state of foraminiferal protoplasm is by observation of pseudopodial action or cytological sectioning and staining of the nuclei. Neither of these methods appears to be adaptable to ecological studies for geological and oceanographic purposes, owing to the specialized equipment and techniques required in such procedures and the large amount of material that must be examined in the course of an ecological study. The methods used in the past to differentiate between living and dead Foraminifera and the one presently being used are attempts to approximate living populations, and the results obtained are conditioned by certain basic assumptions.

Color Reactions For Protein

In concluding that a protein color reaction is a positive indication of a living organism, it must first be assumed that: 1) the color reaction is reliable, 2) the presence of protein within the shell is a positive indication of the presence of protoplasm, and 3) the presence of protoplasm is positive indication of a living or very recently dead organism. The color reactions for protein as described above are standard procedures used in physiological chemistry for protein tests and have been adapted for this particular problem. If the tests are carefully conducted there is no reason to doubt their accuracy as indicators of protein, and it appears certain that the presence of native protein does indicate the presence of protoplasm. It is generally accepted that foraminiferal protoplasm is amoeboid in structure and contains the constituent radicals to which the color reactions are sensitive. Hawk and Bergeim (1937, p. 147) point out that "various substances not proteins respond to certain of these color reactions." These "substances" will not be considered here, but the probability of their occurrence in Foraminifera shells is negligible.

The third assumption involves the rate of decay of organic material, including protoplasm, in the ocean. The life cycle of the Foraminifera does not involve natural death of mature specimens. Continuous growth and sexual and asexual reproduction in these Protozoa are infinite processes, barring the interference of external agents of death. If the animals are eaten by other animals, which is certainly the fate of many Foraminifera, the protoplasm would disintegrate on contact with intestinal fluids. If we assume, however, that the animals are killed *in situ* by some radical change in physical environment, what would be the fate of the protoplasm? Considerable work on the rate of decay of organic material in marine sediments has shown that bacterial decomposition of such protoplasm is extremely rapid, the material remaining as recognizable protoplasm for a very brief period. (ZoBell, 1948, p. 138, 143). Even if it is assumed that a small proportion of the Foraminifera which reacted positively to color tests are recently dead (within a few days) they may be enumerated among the living specimens.

The usefulness of the protein tests and the degree of coloration varies. Millon's reagent contains free nitric acid and is limited in its use to arenaceous faunas. It has been used in the past (Phleger, 1952) on sediment samples after a preliminary examination to check for calcareous specimens. The samples on which the Millon's reagent was used contained very ew calcareous specimens and these were counted beore the addition of the reagent. The red color obained in this test is definite but breakage of most of he arenaceous specimens was required for identificaion of protein. The principal disadvantage of the ILLON's reaction is its restricted usefulness.

The Biuret reaction has been used more extensively n this country than any of the other methods. It has been used with considerable success on both planktonic and benthonic Foraminifera (Phleger, 1945, 1951). The primary objection to the use of the Biuret reaction is the relatively weak and temporary nature of the coloration. At maximum coloration, the color varies from blue to pink and frequently the tests must be broken to detect the protein; the permanency of the color varies with the concentration of the hydroxide in the Biuret solution. In recent observations, using a stable Biuret solution, maximum coloration was obtained in approximately 20 to 30 minutes with complete decoloration in from 1 to 2 hours after the solution had been added to the sample. In previous experiments, however, the color remained from 4 to 6 hours. The Biuret reagent can be used on both calcareous and arenaceous forms.

The Stain Tests

The use of a biological stain often requires the knowledge of special techniques and equipment, but only because of the complexity of the substances being stained, not because of the complexity of the staining process. The theory of staining is the same as that of any common dyeing process. The stain selected for any particular use is done so experimentally, according to the coloration desired and the affinity of the stain for the structure or substance under consideration. By virtue of this characteristic of stains, the assumption underlying their use as diagnostic indicators of living Foraminifera is that stain has an affinity for protoplasm. It is assumed that the presence of protoplasm indicates that the specimen was alive when collected or only recently dead, as discussed above. The substances that have been observed to occur on or in both living Foraminifera and empty tests are as follows: calcite, silica, "chitin," iron oxide, detrital minerals, organic and inorganic debris, algae, and foraminiferal protoplasm. The accuracy of the assumption will be determined by the selectivity of the stain for protoplasm.

Rhumbler's technique is not satisfactory for rapid identification of living Foraminifera in sediment samples. The "Methgreosin" solution stains everything in a sediment sample, including "chitin," fecal material, and detritus (Rhumbler, 1935, p. 145). Although the sediment and living animals are differentiated colorimetrically in the staining process, it is undesirable to have all the material stained. In ecological studies for geological purposes the animals, living or dead, must be regarded as constituents of the sediment sample. The information obtained from quantitative studies of living Foraminifera must be considered collaterally with other sediment characteristics; the emphasis is not on the living animal alone but on the living animal in association with the other sediment characteristics. A stain solution which obscures or alters the sediment characteristics is not desirable for ecological studies even though it distinguishes between living animals and empty tests.

Many stains are available which could be used to stain isolated specimens of living or preserved Foraminifera. One of the purposes of this study has been to find a stain which could be applied to living Foraminifera in a washed sediment sample without incidental staining of organic or inorganic debris. Many stains and combinations of stains were tried, none of which was satisfactory, because of their nonselective action.

At the suggestion of H. J. CONN of the Biological Stain Commission, the higher homologs of eosin (philoxine, erythrosin, and rose Bengal) were tried. Rose Bengal was found to fulfill more closely the specifications of a foraminiferal stain than any other. A series of experiments involving various concentrations of the stain in aqueous solution were conducted on preserved samples from the Gulf of Mexico, the coast of California, and freshly collected samples from the La Jolla, Calif., area. Rose Bengal stained only organisms which were living at the time of collection. Worms, arthropods, and Foraminifera shells containing protoplasm were stained a deep rose, leaving empty shells, organic and inorganic debris unstained. Several specimens of copepods and hydroids were stained with rose Bengal to determine the effect of this stain on "chitin." It was found to impart a pink tint to "chitin" but this color is in contrast to the deep rose color obtained on living protoplasm, hence no difficulty is encountered in distinguishing the two degrees of coloration. The color of the stained protoplasm can be clearly seen through the arenaceous tests of such species as *Arenoparrella mexicana* (KORNFELD), *Miliammina fusca* (H. B. BRADY), and *Trochammina inflata* (MONTAGU) in wet samples, and is plainly visible through the walls of calcareous specimens.

It is believed that enumeration of living animals with the use of rose Bengal is within the accuracy of known sampling and counting techniques. Many inherent errors are present in any population count: it is generally assumed, perhaps erroneously, that a given sample is representative of a given area many times its diameter; the condition of the protoplasm of the living animal at the time of collection may vary; various states of maturity and reproduction must be present in a given sample, and these stages may give different stain characteristics; a personal counting and identification error is also inherent in population counts.

It is apparent that we need not seek greater accuracy in determinations of living specimens as long as our results are conditioned by the above variables. Attempts are presently being made to increase the accuracy of population counts and to define and limit the variables indicated above.

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61. FORAMINIFERA DISTRIBUTION IN SOME SEDIMENT SAMPLES FROM THE CANADIAN AND GREENLAND ARCTIC

FRED B PHLEGER

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61. FORAMINIFERA DISTRIBUTION IN SOME SEDIMENT SAMPLES FROM THE CANADIAN AND GREENLAND ARCTIC

Fred B Phleger

SUMMARY

1. - Foraminifera populations have been analyzed in 49 bottom sediment samples from the Greenland and Canadian Arctic from approximately 70° N. Lat. to 80° N. Lat. and from 59° W. Long. to 112° W. Long.

2. - Planktonic Foraminifera are present at only one-third of the stations, and consist principally of *Globigerina pachyderma* (Ehrenberg) with smaller populations of *G. bulloides* Orbigny and juvenile globigerinids.

3. - The benthonic Foraminifera-fauna is a character-

istic Arctic assemblage, is essentially uniform throughout the region, and is dominated by the following species:

Cassidulina norcrossi Cushman
Cibicides lobatulus (Walker and Jacob)
Elphidium incertum (Williamson) and vars.
Eponides frigidus (Cushman)
Haplophragmoides glomeratum (Brady)
Proteonina atlantica Cushman
Spiroplectammina biformis (Parker and Jones)
Textularia torquata Parker (Ms.).
Trochammina nana (Brady)

4. - There are indications of depth zonation in Baffin Bay, Lancaster Sound, Melville Sound, and at some of the shallow-water harbor areas. Mixing of faunas is attributed to ice-rafting. It is suggested that the occurrence of considerable quantities of shallow-water sedimentary materials transported into deep water by ice-rafting and there mixed with sediments more normal to this zone may be one of the main characteristics of Arctic marine sediments.

. - It is demonstrated that the faunas from different parts of this region can be distinguished from each other.

INTRODUCTION

The Foraminifera discussed in this paper are from 9 marine sediment samples collected by members of he United States Coast Guard aboard the USS ORTHWIND during the summer of 1947. All the amples are from the Canadian and Greenland Arctic, nd are within a region extending from approximately 1° N. Lat. to 80° N. Lat. and 59° W. Long. to 12° W. Long. The purposes of the present study are s follows:

1.) to record in quantitative terms the Foraminifera opulations in samples taken from a region where the oraminifera are little known, and

2.) to analyze any general geographic variations or milarities which may exist in these populations.

The writer acknowledges with gratitude the cooper- ion of the U. S. Coast Guard and the captain of the SS NORTHWIND in collecting the samples and mak- g them available for study. Much of the work in udying this material has been done by Frances L. rker and Jean F. Peirson. The laboratory work has en financed by the Office of Naval Research under ject NR 081 050.

METHODS

Twenty-one of the samples were collected using a varf orange-peel dredge having a rated capacity of 0 cu. in. The dredge was covered with a canvas od to prevent washing of the sediment sample en- ute to the surface. It was further modified with a pping device so that it can be operated from one re in place of the two wires usually employed. A presentative portion for laboratory study was saved from the relatively large sample collected with this instrument.

Eighteen samples were collected with the bottom sediment sampler designed by Phleger (1951). This gear obtains a short core emplaced in a plastic tube and recovers material from a known and constant area of the actual surface of the bottom in a relatively undisturbed condition. The surface sediment in the short cores was treated with formaldehyde to preserve the living population of Foraminifera.

The fauna from a thickness of 1 cm. of the top of each core was studied. The presence of Foraminifera which were alive when the sample was collected was determined by the biuret test for protein as follows: The bottom sample is washed over a #200 brass sieve until it is free from mud and is then placed in a test tube with a small amount of water. An approximately equal amount of 10% sodium hydroxide is added and the solution is allowed to stand for 10 minutes. 30 to 60 drops of 0.5% copper sulfate solution are added, with vigorous agitation of the solution after each 3-5 drops. The solution is placed in a petri dish marked off with a grid pattern. Protoplasm, colored purple or pink, is best seen against a white background with a properly adjusted light source.

After examination for living specimens the sample is thoroughly washed and dried, and the population in the dry sample is studied. Counts are made of the species and either the entire population is counted or a total population estimate is made from the count of a fraction of a large sample.

DISTRIBUTION OF SPECIES

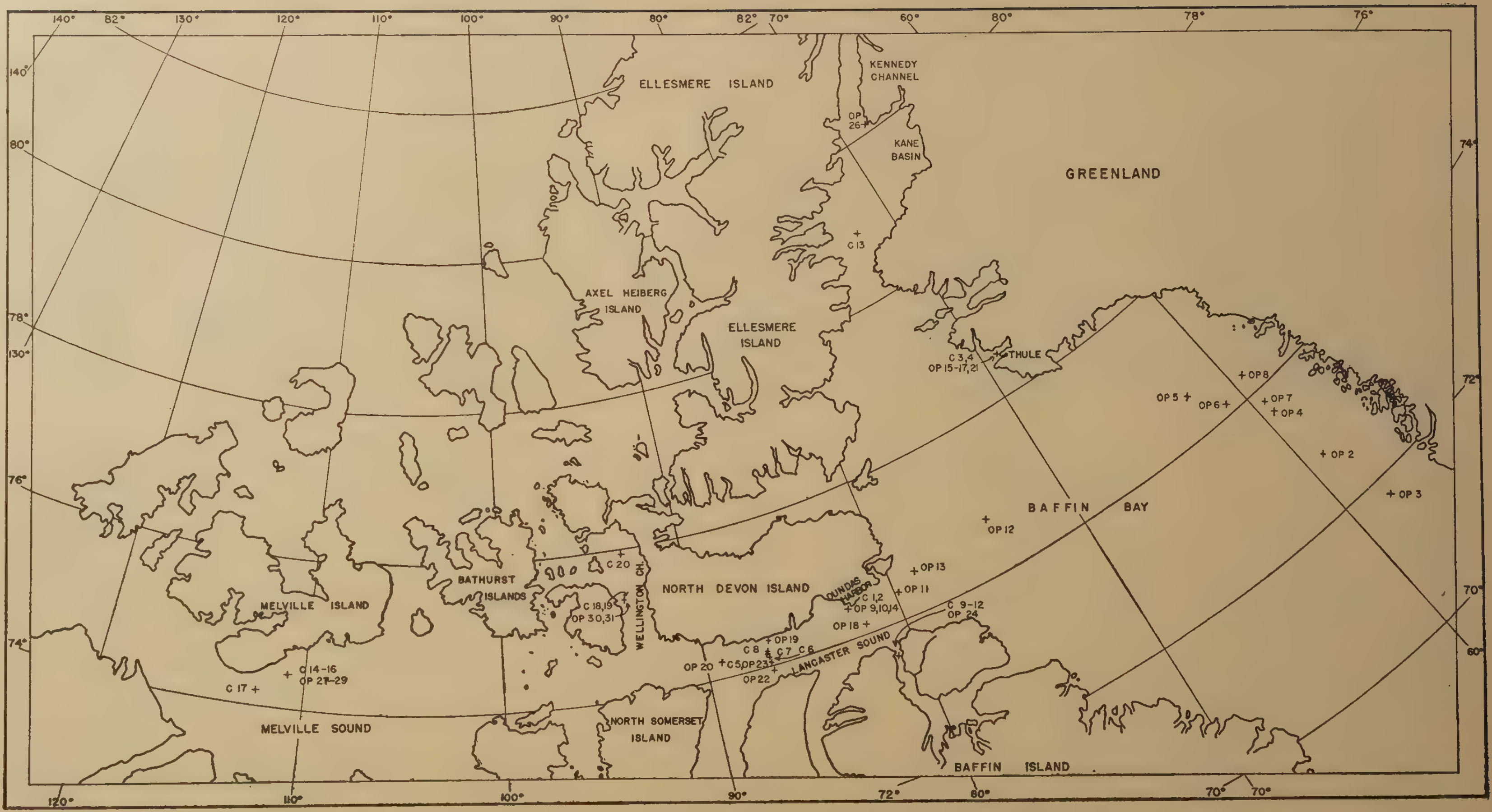
PLANKTONIC FORAMINIFERA

Planktonic Foraminifera are recorded from 18 of the stations in low frequencies except at station C 3 where there is an estimated population of approximately 2500 specimens. The most common species is *Globigerina pachyderma* (Ehrenberg), a typically Arctic and sub-Arctic form. *Globigerina bulloides* Orbigny is the only other recognizable planktonic species. Unidentifiable young *Globigerina* occurs at several stations.

BENTHONIC FORAMINIFERA

The assemblage of benthonic Foraminifera consists of at least 45 species which occur in significant abundance at several stations. The benthonic fauna for the region as a whole is dominated by the following species, listed in alphabetical order:

Cassidulina norcrossi Cushman
Cibicides lobatulus (Walker and Jacob)
Elphidium incertum (Williamson) and vars.
Eponides frigidus (Cushman)
Haplophragmoides glomeratum (Brady)
Proteonina atlantica Cushman
Spiroplectammina biformis (Parker and Jones)
Textularia torquata Parker (Ms.)
Trochammina nana (Brady)


GREENLAND
KENNEDY CHANNEL
KANE BASIN
OP 26
ELLESMERE ISLAND
C 13
AXEL HEIBERG ISLAND
ELLESMERE ISLAND
C 3,4
OP 15-17,21
THULE
OP 8
OP 5
OP 6
OP 7
OP 4
OP 2
OP 3
BAFFIN BAY
OP 12
OP 13
OP 11
NORTH DEVON ISLAND
DUNDAS HARBOR
C 1,2
OP 9,10,14
C 9-12
OP 24
OP 18
OP 19
C 8
C 7
C 6
OP 20
C 5, OP 23
OP 22
LANCASTER SOUND
C 20
WELLINGTON CH.
C 18,19
OP 30,31
BATHURST ISLANDS
MELVILLE ISLAND
C 14-16
OP 27-29
C 17
MELVILLE SOUND
NORTH SOMERSET ISLAND
BAFFIN ISLAND
140°
82°
130°
120°
110°
100°
90°
80°
82°
70°
60°
80°
78°
76°
74°
72°
70°
60°
70°
70°
80°
72°
90°
100°
110°
120°
140°
80°
78°
130°
76°
74°

Text Fig. 1. CHART SHOWING THE LOCATIONS OF THE STATIONS

The distribution chart of species appears as Table 1; individual species distributions are discussed below.

Ammobaculites cassis (Parker). At only 7 stations in frequencies usually less than 2%, except at one station in Toy Bay where it is 24% of fauna. Most occurrences in Dundas Harbor and Burnett Creek, but also present in 1 sample each in Baffin Bay, Lancaster Sound and Toy Bay.

This species is reported in the Atlantic from Barnstable, Mass., and from off Portsmouth, N. H., but the specimens are not typical. It also occurs in the Pacific, according to Cushman, from north of the New Siberian Islands in the Russian Arctic, off Nova Zembla, and from off Alaska in very shallow water. It is probably a very shallow-water form, usually occurring at less than about 20 fathoms.

Ammodiscus gullmarensis Höglund. Frequencies up to 6% but usually 1% or less. Occurs at most stations in Thule and Lancaster Sound, and present at 1 station in Baffin Bay, 2 stations in Wellington Channel, and 3 stations in Melville Sound.

Höglund has reported this species from Gullmar Fjord, off Sweden, at 24-79 meters.

Angulogerina angulosa (Williamson). Usual frequencies 5% or less but 10% at one Thule station. Not present in Dundas Harbor, Toy Bay, and Melville Sound.

This species is widespread in the Atlantic. It is abundant off the northeast coast of the U. S., but probably does not occur south of Cape Hatteras. It has no facies significance according to Parker (1948). It is reported as rare in the Antarctic but abundant around the Falklands; occurs at numerous stations between Alaska and the Guadalupe Islands.

Astrononion stellatum Cushman and Edwards. Frequencies 5% or less and occurs at numerous stations except in Toy Bay.

This species is widely distributed in the colder parts of the North Atlantic. It is reported from off Newfoundland, Iceland, and from the southwest Gulf of Maine. It does not occur south of Cape Cod.

Bolivina pseudopunctata Höglund. 4% or less in Lancaster Sound, Dundas Harbor, and Wellington Channel, with one occurrence at Thule.

Previously reported from Gullmar Fjord at 26-118 m., and the Skagerrak deeper than 500 m. It is present in the Portsmouth, N. H. area at 4 shallow stations.

Cassidulina islandica Nørvang var. *minuta* Nørvang.[1] Common at many stations throughout the region except in Toy Bay and 1 occurrence only in Melville Sound. Highest frequencies in Dundas Harbor, up to 33%.

This species is rare off Portsmouth, N. H., in the southwest Gulf of Maine, and has been reported from off Iceland.

Cassidulina norcrossi Cushman. High frequencies at most stations except Toy Bay and only 1 occurrence in Melville Sound, with greatest abundance at Thule, Dundas Harbor, and Wellington Channel (up to 43%).

This species is reported previously from off Greenland and Iceland. On the continental shelf of the western Atlantic it reaches its greatest frequency below 300 m.

Cibicides lobatulus (Walker and Jacob). Abundant at many stations and generally distributed throughout the area. Highest frequency in Kane Basin (61%), with frequencies up to 25% at some stations in Lancaster Sound, Dundas Harbor, and Wellington Channel.

This is a very widespread attached form, probably characteristic of shallow water.

Cribroelphidium bartletti (Cushman). Only known from 2 stations in Dundas Harbor and 1 station at Burnett Creek, with frequencies up to 12%.

This species is reported from Puget Sound by Cushman and Todd. Many of the specimens reported from the Arctic as *Nonion orbiculare* may belong here.

Discorbis sp. Principal occurrence in Dundas Harbor at 2% or less. 1% or less at 1 station in Kane Basin and Wellington Channel, and at 2 stations in Lancaster Sound.

Eggerella advena (Cushman). Principally restricted to Dundas Harbor and Thule but present at 1 station in Baffin Bay, Lancaster Sound and Burnett Creek. Highest frequencies are at Thule where they range from 12% to 50%.

This species occurs around the British Isles, off Scandinavia, and occurs shallower than 90 m. in the western Atlantic. It is also present in the Portsmouth, N. H. area, rarely in the Antarctic, and is present in the eastern Pacific from Alaska to Peru.

Elphidiella arctica (Parker and Jones). Occurs at 6 stations with frequencies of 4% or less; 1 station in Baffin Bay, 1 in Kane Basin, 1 at Dundas Harbor, and 3 stations in Wellington Channel.

This species is previously reported from Hudson Bay, Iceland, and off the New England coast. It is not reported from the Antarctic.

Elphidium incertum (Williamson) and vars. Generally distributed except in Toy Bay and Melville Sound. Highest frequencies in Dundas Harbor, Burnett Creek, and Wellington Channel, ranging up to 25%. Less abundant (where it occurs) in other areas.

This species is widely distributed in the Arctic and North Atlantic.

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[1] Note by Editor: **Cassidulina islandica** Nørvang, 1945, forma **minuta** Nørvang, 1945, The Zool. of Iceland, vol. 2, pt. 2, p. 43, text figs. 8a-c, Recent, off Iceland, regarded as a true variety (or subspecies) by Cushman, 1948, Cushman Lab. Foram. Research, Spec. Publ. No. 23, p. 75-76, is a homonym of **Cassidulina minuta** Cushman, 1933, Cushman Lab. Foram. Research, Contr., vol. 9, p. 92, pl. 10, fig. 3, Recent, Tropical Pacific, and herewith renamed: **Cassidulina islandica** Nørvang, 1945, var. **nørvangi** Thalmann, **nom. nov.**

LOCATION	BAFFIN BAY								THULE						KANE BASIN	KENNEDY CHANNEL	LANCASTER SOUND									DUNDAS HARBOR					TOY BAY					BURNETT CREEK	WELLINGTON CHANNEL					MELVILLE SOUND					
NORTH LATITUDE	72°48'	71°42'	73°37'	74°38'	74°10'	74°46'	73°49'	74°16'	76°38'	76°38'	76°38'	76°38'	76°38'	76°38'	78°53'	80°18'	74°26'	74°38'	73°57'	74°03'	74°18'	74°08'	74°13'	74°32'	74°18'	74°35'	74°35'	74°35'	74°35'	74°35'	73°37'	73°37'	73°37'	73°37'	73°37'	74°25'	75°22'	75°22'	75°22'	75°22'	75°55'	74°34'	74°34'	74°34'	74°34'	74°34'	74°34'
WEST LONGITUDE	58°30'	57°51'	59°32'	62°47'	60°54'	74°25'	59°06'	59°05'	68°48'	68°48'	68°48'	68°48'	68°48'	68°48'	73°35'	67°42'	89°07'	78°28'	87°05'	87°05'	87°05'	87°05'	87°05'	79°50'	82°30'	82°11'	82°11'	82°11'	82°11'	82°11'	80°42'	80°42'	80°42'	80°42'	80°42'	86°45'	93°22'	93°22'	93°22'	93°22'	93°14'	110°40'	110°40'	110°40'	110°40'	110°40'	110°40'
SAMPLE	OP 2	OP 3	OP 4	OP 5	OP 6	OP 12	OP 7	OP 8	OP 15	OP 16	OP 17	OP 21	C 3	C 4	C 13	OP26	OP20	OP 13	OP 22	C 5	C 8	C 6	C 7	OP 11	OP 18	OP 9	OP 10	OP 14	C 1	C 2	OP24	C 9	C 10	C 11	C 12	OP 19	OP30	OP 31	C 18	C 19	C 20	C 14	C 15	C 16	OP27	OP 28	OP 29
DEPTH IN METERS	188	244	230	256	621	629	877	823	31	31	31	31	31	31	124	345	276	391	439	457	449	439	419	592	658	38	31	40	38	38							137	137	155	155	126	124	124	124	124	124	124
TOTAL PLANKTONIC POPULATION	16			1	8								[illegible]	2	2500	210			4						5	10		22	[illegible]	16	1				2						6					6	3
Globigerina bulloides	12														10											100		36		100																	10
G. pachyderma	87			100	100								100		51	88									100			64																			
G. sp.														100	38	12			100										100		100				100						100					100	
TOTAL BENTHONIC POPULATION	900	300	480	250	95	330	65	5	1200	520	85	250	250	300	9500	950	200	450	220	450	270	230	700	450	95	2100	50	3500	4100	2300	1	1	20	15	20	1900	1300	900	500	540	2000	1000	1740	1920	2140	2400	330
Ammobaculites cassis		3																.7								.2	2	.06	3						24	.5											
Ammodiscus gullmarensis				.8					.2		1	6	.9				2	.7	3	1	1	4	2	5														.1	.4					.4	.1	.2	
Angulogerina angulosa	2	2							.2			10				.5	5	3			.4		4														.5	.1	.4								
Astrononion stellatum	1	.7							4	6	1	.4			.3	.5	2	1	.9				1	.5		.6		.2								.3		.2	2						.05		
Bolivina pseudopunctata													.4							.2		.4	3			3		.06	.4	.7									2	2	.3						
Cassidulina islandica minuta	.6	4							.2	5	8		2		1	9	4						.7	2	2	.2	2	19	33	25						20	2	2	4	2	9						2
C. norcrossi	6	8		.4	1				16	18	15	11	.4		1		24	10	7		.4		2	3	5	20	2	17	13	6						16	43	43	44	38	10						2
Cibicides lobatulus	14	.7	.4		4				.3			.8			61	10	1	.4					1	18	34	1	22	7	5	10	100					4	22	25	6	4	17				.4	.2	.6
Cribroelphidium bartletti																											9			.3						12											
Discorbis sp.															1								6		1	1	2	2	.4												.3						
Eggerella advena			13						39	50	26		15	12						2						5	4	4								4											
Elphidiella arctica	.4														4												2										.5		.4		1						
Elphidium incertum & variants	2	.7							2	6		2	3		1	7		1	3					5	4	13	15	32	24	26						25	6	4			12						
E. subarcticum	4	.7							1	2			.4		1	1		.2						9		7	6	3	.8	3						5	.5	2	6	3	13						
Eponides frigidus	5	1					4		1	4	2	3	.4		12	3	17	4	5		2		4	1	2	.9	17	4	2	2						6	9	10	6	5	6						
Globobulimina auriculata arctica	.7																				.4																										
Haplophragmoides glomeratum	32	44		14	1	12	20		.8	.4	2	24		3	4	35	24	39	28	17	20	23	17	36	20			.06									.9	2	2	3		13	14	19	35	30	2
Labrospira arctica				1	2	2	1																					.06																			
L. crassimargo	2	3	.8	16	1	.3			3	1	8		3	1	2	.5						.9	.1	.2		.7		2	.4	1							2	.3	1		.3	11	6	4	20	15	6
L. jeffreysii	1	.7	1	2	2	4			.9					.3	2	5		.4				4	4	2	2		11			.3						.3		.3	.8	.4		5	3	5	5	5	7
Lagenidae, etc.	1								.4	.4	1	.8				2	4	.4	.9				1		1	.2		.06		.3							1	.8	.8	1	.3						
Miliammina groenlandica	.2								.3								.5		.9	3	3	2	1			.2							30	6	33				2	1	.3						
Nonion barleeanum	1	.3		.4	13	2	11		.1			1			1	3		.7	3	.3	3	3		2	1			3																		.6	
N. labradoricum	1						3		1	.8	1	4	.9				1	8	3				.3	2		3			4	1			5			.3	4	3	7	7							
Oolina costata															.7																								.8	.4	.9						
Proteonina atlantica	10	16	5	15	3	8	12		3	3	2	19	2	4	1		3	7	6	8	13	8	3	2		.1		.06						12			.5	.2	2	.7	.3	7	4	5	1	1	
Psammosphaera fusca																																										6	.6	.4	.1		
Recurvoides turbinatus	.6	1	2	2	3	.6	3		.6			.4	.4	.3							.4		1	1	1	.1		1	3	2							.8	1		.4		4	1	4	1		
Reophax arctica			10	.8					2		12		4	5			.5		.5	6	3	1	2			6		6	.4	2					10			.8	.4	2		.4					
R. curtus	1	1	4						4	.4	1			.6	2					.7	.4									.3										.4					.3		
R. guttifera					4	1																																						.4			
R. nodulosa																																										.8	1	.7	1	.6	
R. cf. scorpiurus										.2						.5				1	.4		1												10					.7		6	2	2		.2	
Spiroplectammina biformis	2	5	28	2		.3	3		13	3	4	1	24	33			1	1	5	13	7	4	8		6	11	2	2	.8	2			65	56	14	5	.9		2	6		6	13	7	.1	.1	
Textularia tenuissima		5	2		1	.3						.8			.3	.5			1	5	3	8	3																.4			.8	5	3			
T. torquata		2	32			.3			.8	2	15		39	40	.7	6	.5	.7	4	27	20	15	14	.9	7	1		.6	.8	2				25	10	.3	2		3	15	.9	4	5	2			
Trochammina inflata																													.4													.8	1	.7			
T. nana	7	4		30	46	56	38	60	6			10	2	2		10	3	15	22	11	17	19	14	27	9					.7							.5	.1			.3	27	42	41	33	33	4
T. quadriloba					5			40				1							.9	2	17	4	4									100															
T. squamata			1							.2			.4	.3														.3																			
Trochamminella atlantica	.4				8	2																2															.1					6	2	4	2	8	4
T. bullata				14		10																	.9	2																				.7			
Virgulina cf. complanata	3														.3	2	3	2	4				.7	.2															2	.7							
V. fusiformis		3							.3			.8	3								.4				2	19	2	3	7	21						.3	3	1	5	7	27					.7	

Table 1. Occurrences of Foraminifera in the samples given in percent of total population at each station.

Cassidulina islandica minuta has been renamed: **Cassidulina islandica** Nørvang var. **nørvangi** Thalmann (see p. 83, footnote 1).

Textularia tenuissima will be renamed **Textularia earlandi** by F. L. Parker in a forthcoming paper.

Elphidium subarcticum Cushman. Essentially the same distribution as the *E. incertum* group but the frequencies are lower, generally less than 10%, and none greater than 13%.

Occurs off Portsmouth, N. H., and in Long Island Sound in shallow water and at all depths on the Atlantic continental shelf and upper continental slope. It is reported from the Arctic by Cushman.

Eponides frigidus (Cushman). Common at most stations with frequencies up to 10% but usually less. Not present at Toy Bay and Melville Sound and at only 3 stations in Baffin Bay.

Present in shallow-water facies off Portsmouth,
N. H., and in the open-ocean facies in Long Island
Sound area. Also reported from Hudson Bay, Iceland,
Gaspé Bay, and from all facies on the Atlantic continental shelf.

Globobulimina (Desinobulimina) auriculata (Bailey)
var. *arctica* Höglund. At 1 station in Baffin Bay and
1 station in Lancaster Sound, at less than 1%.

This variety is reported from Spitzbergen, Green-
and, and Baffin Bay.

Haplophragmoides glomeratum (H. B. Brady). Abun-
lant at the majority of stations but does not occur in
Toy Bay and Burnett Creek, and only 1 specimen in
Dundas Harbor. Average frequencies 20% or more
but 1% or less at a few stations. Lowest frequencies
n Wellington Channel.

Reported from the Arctic, North Atlantic, and Gulf
of Mexico. Widespread off Portsmouth, N. H., but not
o abundant near shore.

Labrospira arctica Parker. At 4 stations, at 2% or
ess, in Baffin Bay, and 1 specimen from Dundas Har-
bor. This species is being described by Parker else-
where.

Labrospira crassimargo (Norman). In all areas except
Toy Bay and Burnett Creek with frequencies varying
rom less than 1% to 20%. Most abundant in Mel-
ville Sound where it occurs at all stations in relatively
igh frequencies.

This species has been reported from numerous areas
s *Haplophragmoides major* Cushman. It is widely
istributed off Portsmouth, N. H., is reported from
Eastport, Me., the Grand Banks area, an open-ocean
acies near Long Island Sound, the British Isles, and
om the Antarctic. It is probably widespread in the
rctic. Höglund reports it from the Gullmar Fjord
nd the Skagerrak, where it ranges from 55 m. to
00 m. water depth.

abrospira jeffreysii (Williamson). At the majority
f stations in all areas except Toy Bay, with usual
equencies 5% or less.

Widely distributed off Portsmouth, N. H., and re-
orted from off Eastport, Me., and from east of Cape
od but not farther south. It is probably widespread
the Arctic, and some reports of *Haplophragmoides*
nariensis Orbigny from shallow stations in the Ant-
ctic by Earland and also Chapman and Parr may
elong here. Also reported from the Gullmar Fjord
d the Skagerrak.

agenidae. Usual frequencies 1% or less but up to
% at a few stations. In all areas except Toy Bay,
urnett Creek, and Melville Sound, and at only 1
ation in Baffin Bay.

iliammina groenlandica Cushman. At 1 station at
hule, 1 station in Baffin Bay, the majority of stations in Lancaster Sound, 1 station in Dundas Harbor, and 3 stations in Wellington Channel, with frequencies of 2% or less. About 30% of the fauna at 2 stations in Toy Bay.

Previously reported from Iceland and other Arctic areas.

Nonion sp. cf. *N. barleeanum* (Williamson). At the majority of stations in Baffin Bay, Kane Basin, Kennedy Channel, and Lancaster Sound. At 2 stations at Thule, 1 station in Dundas Harbor, and 1 station in Melville Sound. Usual frequencies 3% or less except at 2 stations in Baffin Bay where frequencies are more than 10%.

Widely distributed in the North Atlantic.

Nonion labradoricum (Dawson). At most stations at Thule, Lancaster Sound, Dundas Harbor, and Wellington Channel. Also at 2 stations in Baffin Bay and 1 station in Toy Bay. Frequencies are 8% or less.

This species appears to be widespread in the western North Atlantic with the greatest abundance in the more northern areas.

Oolina costata (Williamson). At 3 stations in Wellington Channel and 1 station in Kane Basin. Frequencies less than 1%.

Proteonina atlantica Cushman. Widely distributed at majority of stations in frequencies generally less than 10% but as great as 19%. Not present at Burnett Creek and Kennedy Channel.

Appears to be widespread in the North Atlantic; sometimes reported as *P. difflugiformis* Brady.

Psammosphaera fusca F. E. Schultze. Present only in Melville Sound in frequencies up to 6%.

Widely distributed in the Arctic, according to Cushman, and also reported from off Norway.

Recurvoides turbinatus (H. B. Brady). Present at numerous stations in all areas except Kane Basin, Kennedy Channel, Toy Bay, and Burnett Creek. Frequencies 4% or less.

This species is very common off Portsmouth, N. H., and is reported by Parker from the Atlantic continental shelf. Earland records it as rare in the Antarctic.

Reophax arctica H. B. Brady. At the majority of stations in all areas except Burnett Creek, Kane Basin, and Kennedy Channel. Frequencies up to 10%.

Present in the Gulf of Maine but not reported south of Cape Cod.

Reophax curta Cushman. At a few stations in all areas except Kennedy Channel, Toy Bay, and Burnett Creek. Frequencies up to 4%.

This species is reported from the British Isles, the Arctic, Gulf of Maine, and the open-ocean facies near Long Island Sound. It may be present in the Antarctic.

Reophax guttifera H. B. Brady. At 2 stations in

Baffin Bay and 2 stations in Melville Sound. Frequency up to 6%.

Appears to be widespread in the Atlantic, according to published reports. Reported from Spitzbergen.

Reophax nodulosa H. B. Brady. Occurs in all samples in Melville Sound with frequencies up to 4%. No other occurrences noted in samples studied.

This species has a wide distribution in deep water, according to Brady.

Reophax sp. cf. *R. scorpiurus* Montfort. At majority of stations in Melville Sound and at 7 other widely distributed stations. Frequency up to 10%.

Spiroplectammina biformis (Parker and Jones). Generally common throughout the region but not recorded from Kane Basin or Kennedy Channel. Average frequencies up to about 10%, but may be more than 50%. The dominant species in Toy Bay.

This species has a wide distribution in Arctic and sub-Arctic areas. It is very abundant in the Gulf of Maine off Portsmouth, N. H., and very rare south of Cape Cod. It is previously reported from off Greenland, Davis Strait, Gulf of St. Lawrence, the British Isles, Franz Josef Land, the Russian Arctic, and off the coast of Washington. It is reported as rare in the Antarctic.

Textularia earlandi Parker (Ms.).[2] At approximately half the stations, but not present in Dundas Harbor, Toy Bay or Burnett Creek. Frequencies up to 50%.

Reported by Earland as rather widespread in the Antarctic and also present around the Falklands. Chapman and Parr report it as rare in a few of their Antarctic samples. It is abundant in the Skagerrak and Kattegat. Reported from the Mediterranean.

Textularia torquata Parker (Ms.). Abundant at the majority of stations with frequencies as high as 40%.

Common off Portsmouth, N. H., where it is described.

Trochammina conica Earland. Only 1% at station C 16, and the first time reported from outside the Antarctic.

Trochammina inflata (Montagu). At 4 stations in Melville Sound and 1 station in Dundas Harbor with frequencies of 2% or less.

This species is a brackish water indicator on Cape Cod, Long Island Sound, and elsewhere. It is recorded from both sides of the Atlantic and from the Pacific from Alaska to Ecuador.

Trochammina nana (H. B. Brady). Abundant at most stations in Baffin Bay, Lancaster Sound, and Melville Sound with frequencies up to 50% or more. At 4 stations at Thule with frequencies up to 10%. At 1 station in Dundas Harbor and 3 stations in Wellington Channel with frequencies less than 1%. Not found in Toy Bay, Burnett Creek, or Kane Basin.

This species is reported as widespread in the Arctic and Antarctic.

Trochammina quadriloba Höglund. At 5 stations in Lancaster Sound with a frequency up to 17%. Also at 1 station at Thule and 1 station in Baffin Bay.

Occurs at numerous stations in the southwest Gulf of Maine and also reported off Sweden.

Trochammina squamata Parker and Jones. At 1 sta-

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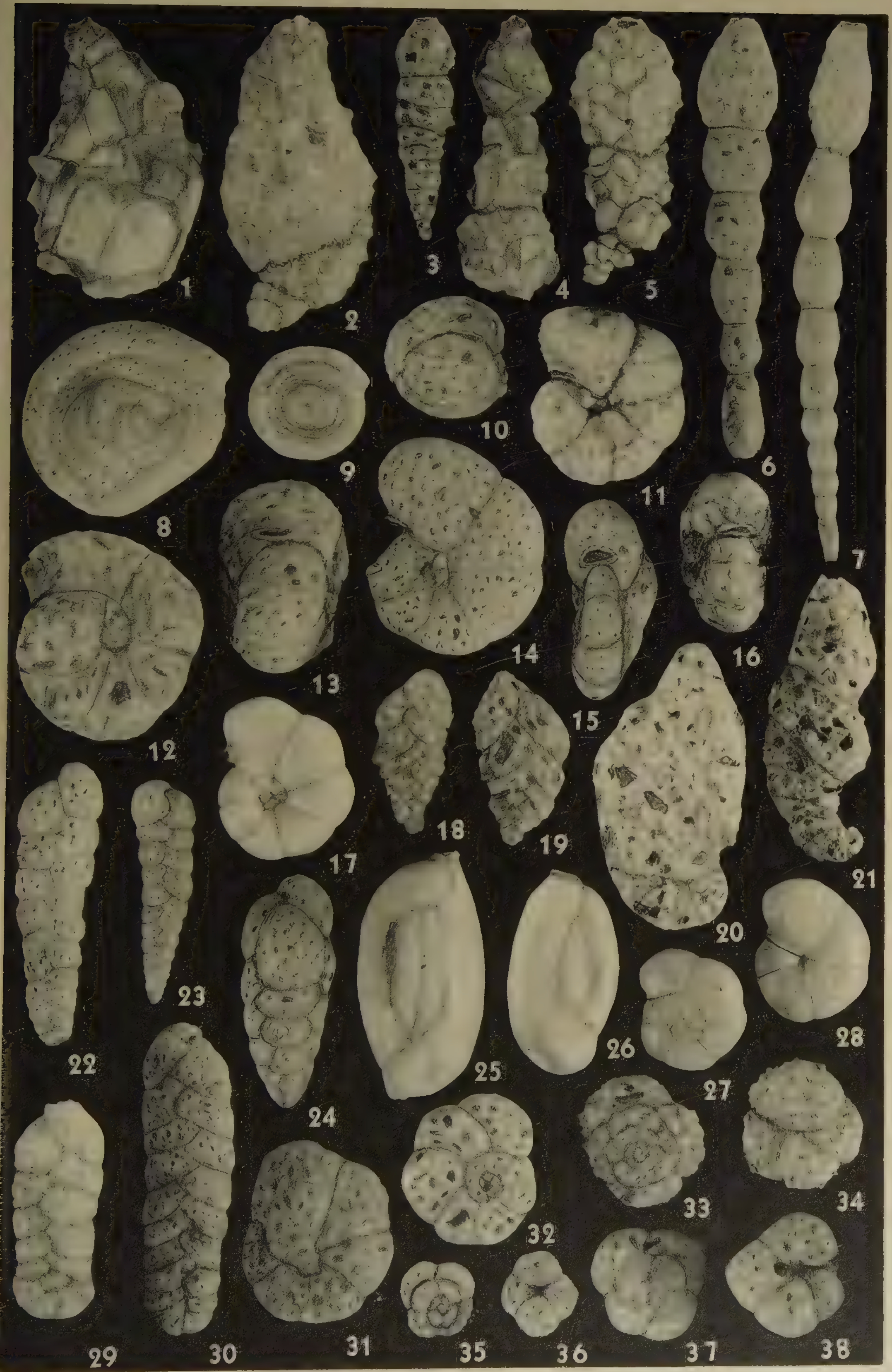
[2] This manuscript name, **Textularia earlandi** Parker, will shortly be published on account of homonymy of **Textularia tenuissima** Earland, 1933, Discovery Repts., vol. 7, p. 95, pl. 3, figs. 21-30, Recent, Antarctic, off South Georgia, with **Textularia tenuissima** Häusler, 1881, Diss. (Thesis), Univ. Zurich, p. 40, pl. 2, fig. 75, Sequanian, Switzerland. (Editor's note).

EXPLANATION OF PLATE 13

Figs.		Page
1.	*Proteonina atlantica* Cushman. × 68. OP 22.	85
2.	*Reophax curtus* Cushman. × 27. OP 15.	85
3.	*Reophax arctica* H. B. Brady. × 94. OP 9.	85
4.	*Reophax guttifera* H. B. Brady. × 68. Core 17.	85
5.	*Reophax sp.* cf. *R. scorpiurus* Montfort. × 27. Core 17.	86
6, 7.	*Reophax nodulosa* H. B. Brady. (6) × 68; (7) × 27. Core 17.	86
8, 9.	*Ammodiscus gullmarensis* Höglund. (8) × 94; (9) × 68. Core 8.	83
10.	*Haplophragmoides glomeratum* (H. B. Brady). × 68. OP 27.	85
11, 16.	*Labrospira crassimargo* (Norman). × 27. OP 27.	85
12, 13.	*Recurvoides turbinatus* (H. B. Brady). × 94. (12) Core 1; (13) OP 4.	85
14, 15.	*Labrospira jeffreysii* (Williamson). × 68. OP 27.	85
17.	*Labrospira arctica* Parker. Holotype. × 68. OP 12.	85
18, 19.	*Textularia torquata* Parker (ms.). × 94. (18) OP 4; (19) Core 13.	86
20, 21.	*Ammobaculites cassis* (Parker). × 27. (20) OP 10; (21) Core 1.	83
22, 23.	*Textularia earlandi* Parker (ms.). (22) × 94; (23) × 68. OP 3.	86
24.	*Eggerella advena* (Cushman). × 68. OP 10.	83
25, 26.	*Miliammina groenlandica* Cushman. × 94. Core 12.	85
27, 28.	*Trochammina inflata* (Montagu). × 94. Core 13.	86
29, 30.	*Spiroplectammina biformis* (Parker and Jones). × 68. OP 4.	86
31, 32.	*Trochammina nana* (H. B. Brady). × 94. OP 7.	86
33, 34.	*Trochammina quadriloba* Höglund. × 94. Core 7.	86
35, 36.	*Trochammina conica* Earland. × 94. Core 16.	86
37, 38.	*Trochamminella bullata* Höglund. × 94. OP 5.	87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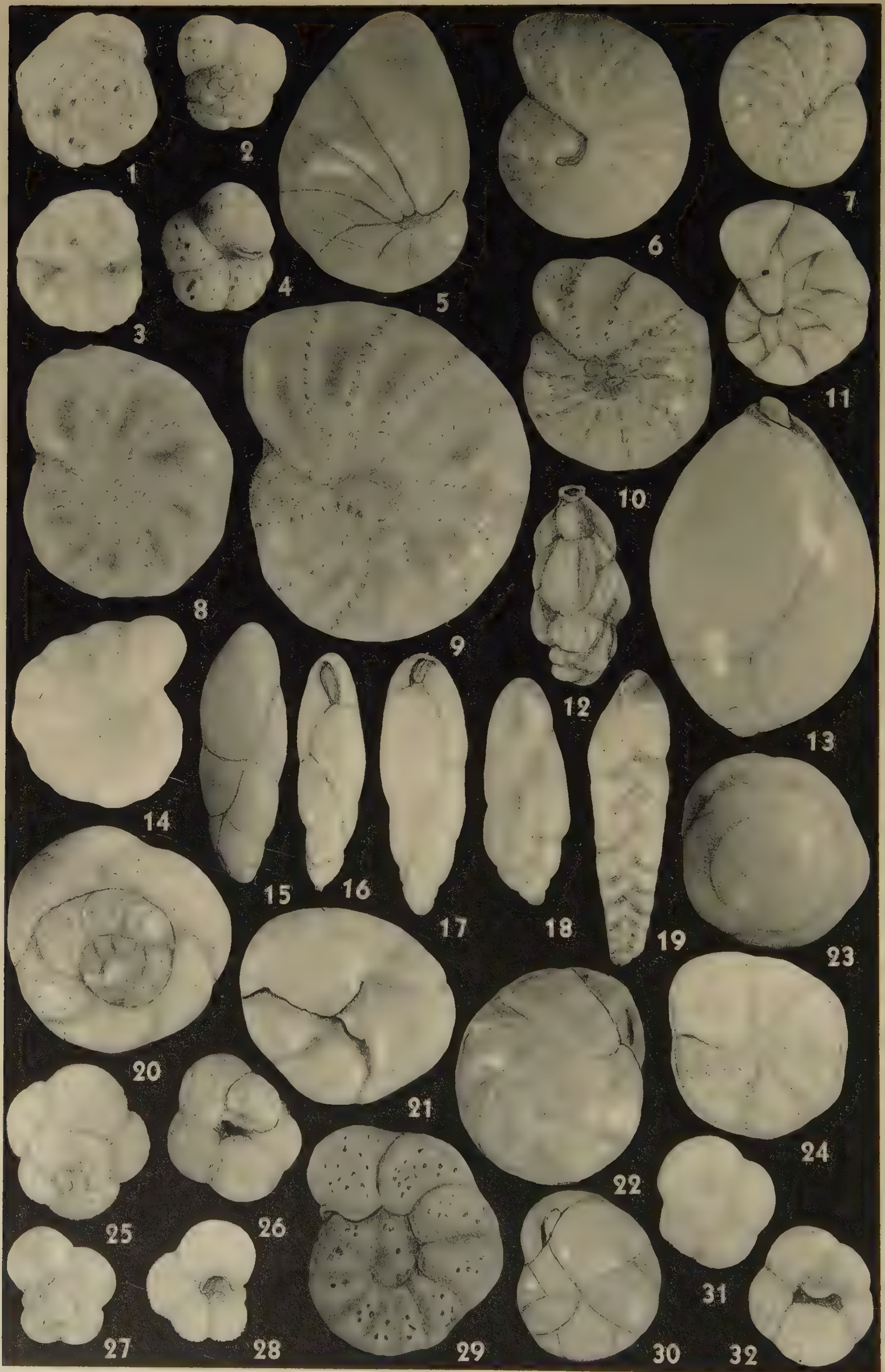
Phleger, Canadian and Greenland Arctic Foraminifera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Phleger, Canadian and Greenland Arctic Foraminifera tion in Baffin Bay, 3 stations at Thule, and 1 station in Dundas Harbor. 1% or less of the fauna.

This species is abundant in the southwest Gulf of Maine. It is previously recorded from the Arctic, Davis Strait, and from deep-water Atlantic samples.

Trochamminella atlantica Parker. At most stations in Melville Sound, 1 station in Wellington Channel, 1 station in Lancaster Sound, and 3 stations in Baffin Bay. Up to 80% of the fauna where present.

Trochamminella bullata Höglund. At 2 stations in Baffin Bay with frequencies up to 14%, 2 stations in Lancaster Sound at less than 10%, 1 station in Wellngton Channel at less than 10%, and 2 stations in Melville Sound with a frequency at 1 station of 24%. Previously reported from the Skagerrak.

irgulina sp. cf. *V. complanata* Egger. Most common n Lancaster Sound at 4% or less. Also present at 1 tation in Baffin Bay, at Kane Basin, Kennedy Channel, and at 2 stations in Wellington Channel.

irgulina fusiformis (Williamson). At all stations in undas Harbor, Wellington Channel, and Burnett reek with frequencies up to 27%. Also at 1 station n Baffin Bay, 3 stations at Thule, 2 stations in Lanaster Sound, and 1 station in Melville Sound at 3% r less of the fauna.

This species is reported from the southwest Gulf of Iaine, from the Atlantic continental shelf, the British sles, and off Sweden.

IVING BENTHONIC FORAMINIFERA

The surface sediment of the core samples was treated vith formaldehyde for identification of specimens vhich were alive when the samples were collected. iving specimens were identified from about half of the core samples. Living specimens were most abundant in Lancaster Sound where they were present in significant abundance in all core samples. They are recorded also from all stations in Wellington Channel and from 1 station at Thule and 1 station in Dundas Harbor.

Proteonina atlantica Cushman was the most common living species; in addition, specimens of the following also were identified:

- *Angulogerina angulosa* (Williamson)
- *Cassidulina islandica* Nørvang var. *minuta* Nørvang
- *Cibicides lobatulus* (Walker and Jacob)
- *Elphidium subarcticum* Cushman
- *Eponides frigidus* (Cushman)
- *Globobulimina auriculata* (Bailey) var. *arctica* Höglund
- *Haplophragmoides glomeratum* (Brady)
- *Labrospira crassimargo* (Norman)
- *Nonion barleeanum* (Williamson)
- *N. labradoricum* (Dawson)
- *Reophax sp.* cf. *R. scorpiurus* Montfort
- *Trochammina nana* (Brady)

This is the approximate percentage representation of living species usually found in a fauna sampled by the methods used and with this frequency of sampling. It is believed that living specimens would have been discovered of all species recorded if sufficient material had been collected and examined.

INTERPRETATION OF FAUNAS

The number of sediment samples collected is insufficient for any definitive study of microfaunal distributions in so large an area. The faunas are so relatively consistent for the region as a whole, however, that the

EXPLANATION OF PLATE 14

IGS.		PAGE
1, 3.	*Trochammina squamata* Parker and Jones. × 94. (1) OP 10; (3) OP 14.	86
2, 4.	*Trochamminella atlantica* Parker. Paratypes. × 68. Core 16.	87
5.	*Nonion labradoricum* (Dawson). × 68. OP 9.	85
6.	*Nonion sp.* cf. *N. barleeanum* (Williamson). × 68. OP 11.	85
7.	*Elphidium incertum* (Williamson). × 68. Core 20.	83
8.	*Elphidium subarcticum* Cushman. × 68. OP 10.	84
9.	*Cribroelphidium bartletti* (Cushman). × 68. OP 10.	83
10.	*Elphidium incertum* (Williamson) var. *clavatum* Cushman. × 68. OP 10.	83
11.	*Astrononion stellatum* Cushman and Edwards. × 68. OP 15.	83
12.	*Angulogerina angulosa* (Williamson). × 94. OP 21.	83
13.	*Globobulimina (Desinobulimina) auriculata* (Bailey) var. *arctica* Höglund. × 68. OP 2.	85
14.	*Elphidiella arctica* (Parker and Jones). × 28. Core 13.	83
5, 16.	*Virgulina sp.* cf. *V. complanata* Egger. × 94. (15) OP 2; (16) Core 13.	87
7, 18.	*Virgulina fusiformis* (Williamson). × 94. OP 9.	87
19.	*Bolivina pseudopunctata* Höglund. × 94. OP 9.	83
21.	*Discorbis* sp. × 68. Core 13.	83
22.	*Cassidulina norcrossi* Cushman. × 68. OP 31.	83
3. 24.	*Eponides frigidus* (Cushman). × 68. OP 30.	84
5. 26.	*Globigerina* sp. × 68. Core 13.	81
7, 28.	*Globigerina bulloides* d'Orbigny. × 68. Core 13.	81
29.	*Cibicides lobatulus* (Walker and Jacob). × 68. OP 14.	83
30.	*Cassidulina islandica* Nørvang var. *nørvangi* Thalmann, nom. nov. × 94. OP 9.	83
1, 32.	*Globigerina pachyderma* (Ehrenberg). × 68. OP 26.	81

results are believed to be more reliable than sample distribution and intensity would suggest. The data and interpretations presented may be modified by study of additional material, but it is believed that the major features of the distributions are essentially correct.

There is a suggestion of some depth zonation in this region, but this is confused by what appears to be faunal mixing of shallow and deep-water sediments. Probable depth zonation is more apparent in Baffin Bay than in Lancaster Sound, the only two areas from which there are samples having a significant depth range. In Baffin Bay the following species appear to be generally indicative of water depths less than about 250 m.:

Angulogerina angulosa (Williamson)
Astrononion stellatum Cushman and Edwards
Cassidulina islandica Nørvang var. *minuta* Nørvang
Cassidulina norcrossi Cushman
Cibicides lobatulus (Walker and Jacob)
Elphidiella arctica (Parker and Jones)
Elphidium incertum (Williamson) and vars.
Eponides frigidus (Cushman)
Miliammina groenlandica Cushman

In general these species show no similar depth restriction in Lancaster Sound, where the depths are somewhat greater, although *Elphidium* is not reported from this area. In Melville Sound there is one relatively deep sample (409 m.) which has a significantly different fauna from the other samples in the area which are from 124 m.

Considerable faunal mixing is obvious in the samples and it is suggested that this is caused by ice-rafting. Faunal mixing and thus absence of clearcut depth zonation may be a characteristic of Arctic areas, especially those areas in which there is considerable shallow water around an intricate coastline. Ice transportation of sedimentary materials, including Foraminifera from near shore zones and later deposition in deeper waters is probably one of the main sedimentary processes in Arctic and Antarctic regions.

The distribution of Arctic Foraminifera has been little studied, and it is not possible to compare the present fauna with others from the Arctic. It is believed that faunas from this region can be differentiated from other Arctic faunas, but it will be necessary to study a great deal of additional material from widely distributed areas before there can be any certainty of this. The present fauna appears to be related to the assemblage near Iceland by having the following species reported from these two regions:

Cassidulina norcrossi Cushman
Cassidulina islandica Nørvang var. *minuta* Nørvang
Elphidiella arctica (Parker and Jones)
Miliammina groenlandica Cushman

The fauna in the southern Gulf of Maine differs by containing numerous species which are also abundant south of Cape Cod.

Sediments from several of the areas covered in this report can be distinguished as to area of origin by distinctive faunal characteristics, such as relative frequencies, restricted distribution of certain species, relative population size, and relative abundance of species. The local faunal differences are relatively minor features superimposed on a general faunal similarity which is characteristic of the region as a whole. Baffin Bay is the one area which does not have any apparent faunal distinction. This may be the result of a large body of water having unlimited communication with several adjacent water areas. Under such conditions faunal mixing may prevent the development of a distinctive assemblage. Additional samples from Baffin Bay, on the other hand, may reveal features which can differentiate it from adjacent areas.

The Thule samples are distinctive in the high percentage of *Eggerella advena* (Cushman) and in the relatively low percentage of *Haplophragmoides glomeratum* (Brady).

The single Kane Basin sample has an unusually high population, an unusually high percentage of *Cibicides lobatulus* (Walker and Jacob), relatively high frequency of *Elphidiella arctica* (Parker and Jones), and also contains *Oolina costata* (Williamson). The Kennedy Channel sample apparently has no distinctive elements.

Lancaster Sound samples have the most persistent occurrences of *Ammodiscus gullmarensis* Höglund. *Trochammina quadriloba* Höglund is essentially restricted to this area, and most of the records of *Virgulina sp.* cf. *V. complanata* Egger are from here. *Nonion barleeanum* (Williamson) is essentially restricted to Baffin Bay and vicinity and Lancaster Sound.

Four of the five samples from Dundas Harbor are characterized by relatively high populations, by the presence of *Ammobaculites cassis* (Parker) and *Discorbis sp.* at most stations, high frequencies of *Elphidium incertum* (Williamson) and vars. at all stations, absence of or very low frequency of *Haplophragmoides glomeratum* (Brady), *Proteonina atlantica* Cushman, *Textularia earlandi* Parker (Ms.), *Textularia torquata* Parker (Ms.), and *Trochammina nana* (Brady), and high frequency of *Virgulina fusiformis* (Williamson).

The Toy Bay Samples have very low populations (20 or less/sample) and a small number of species. The fauna is almost exclusively composed of *Miliammina groenlandica* Cushman, *Spiroplectammina biformis* (Parker and Jones), and *Textularia torquata*, Parker (Ms.).

The Burnett Creek sample has a large population with several species dominated by *Elphidium incertum* (Williamson) and vars., *Cassidulina islandica* Höglund var. *minuta* Höglund, and *Cassidulina norcrossi* Cushman.

The fauna in Wellington Channel is distinct in the igh frequencies of *Cassidulina norcrossi* Cushman, resence of *Elphidiella arctica* (Parker and Jones) at nost stations, low frequencies of *Haplophragmoides lomeratum* (Brady), relative abundance of *Nonion abradoricum* (Dawson), presence of *Oolina costata* Williamson) at most stations, low frequency of *Proeonina atlantica* Cushman and *Trochammina nana* Brady), and relative abundance of *Virgulina fusiormis* (Williamson).

Melville Sound is characterized by the following pecies which are completely or essentially restricted o that area:

Psammosphaera fusca F. E. Schultze
Reophax nodulosa Brady
Reophax sp. cf. *R. scorpiurus* Montfort
Trochammina inflata (Montagu)
Trochamminella atlantica Parker

abrospira crassimargo (Norman) reaches its highest equency here.

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ontributions from the Scripps Institution of Oceanography, New Series, No. 574.

ontribution No. 9 from the Marine Foraminifera Laboratory.

LOCATION OF STATIONS

Orange Peel Samples

No.	Depth-meters	Latitude	Longitude
OP 2	188	72°48′N	58°30′W
OP 3	244	71°42′N	57°51′W
OP 4	230	73°37′N	59°32′W
OP 5	256	74°38′N	62°47′W
OP 6	621	74°10′N	60°54′W
OP 7	877	73°49′N	59°06′W
OP 8	823	74°16′N	59°05′W
OP 9	38	74°35′N	82°11′W
OP 10	31	74°35′N	82°11′W
OP 11	592	74°32′N	79°50′W
OP 12	629	74°46′N	74°25′W
OP 13	391	74°38′N	78°28′W
OP 14	40	74°35′N	82°11′W
OP 15	31	76°38′N	68°48′W
OP 16	31	76°38′N	68°48′W
OP 17	31	76°38′N	68°48′W
OP 18	658	74°18′N	82°30′W
OP 19		74°25′N	86°45′W
OP 20	276	74°26′N	89°07′W
OP 21	31	76°38′N	68°48′W
OP 22	439	73°57′N	87°05′W
OP 24		73°37′N	80°42′W
OP 26	345	80°18′N	67°42′W
OP 27	124	74°34′N	110°40′W
OP 28	124	74°34′N	110°40′W
OP 29	124	74°34′N	110°40′W
OP 30	137	75°22′N	93°22′W
OP 31	137	75°22′N	93°22′W

CORE SAMPLES

No.	Depth-meters	Latitude	Longitude
C 1	38	74°35′N	82°11′W
C 2	38	74°35′N	82°11′W
C 3	31	76°38′N	68°48′W
C 4	31	76°38′N	68°48′W
C 5	457	74°03′N	87°05′W
C 6	439	74°08′N	87°05′W
C 7	419	74°13′N	87°05′W
C 8	448	74°18′N	87°05′W
C 9		73°37′N	80°42′W
C 10		73°37′N	80°42′W
C 11		73°37′N	80°42′W
C 12		73°37′N	80°42′W
C 13	124	78°53′N	73°35′W
C 14	124	74°34′N	110°40′W
C 15	124	74°34′N	110°40′W
C 16	124	74°34′N	110°40′W
C 17	409	74°15′N	112°35′W
C 18	155	75°22′N	93°22′W
C 19	155	75°22′N	93°22′W
C 20	126	75°55′N	93°14′W

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A NEW EOCENE RADIOLARIAN GENUS[1]

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Scripps Institution of Oceanography, La Jolla, California and St. Mary's College, St. Marys, California.

In the course of an examination of Eocene radiolarian faunas of the Mount Diablo area, California, Clark and Campbell (1942) found a few specimens of a form which was described as *Soreuma* (*Soreumium*) *magnificum* Clark and Campbell. Later, an investigation of the Radiolaria from the Kreyenhagen formation (Clark and Campbell, 1945) provided more specimens, and as these latter were better preserved than those from the former locality, and all had radial spines, the subgeneric designation was emended to *Soreumidium.*

A re-examination of specimens from the Kreyenhagen near Los Banos (Locality A 3980, University of California Museum of Paleontology) has shown that this form is not a *Soreuma*, but a dicyrtid Nassellarian for which a new genus must be erected. This work has been made possible through financial aid from the Penrose Bequest of the Geological Society of America.

The distinguishing feature of the genus, and the feature which caused the confusion with *Soreuma*, is the presence of a velum on the under side of the flatly expanded thorax. In the species from the Kreyenhagen formation, this velum is spongy, and underlies a considerable area of the thoracic wall. A related form, to be described in a subsequent paper, has been found in an upper Eocene sediment from the continental slope off New Jersey: the velum in this species is not spongy, but consists of a short, porous, cylindrical tube.

The following description is based entirely on specimens from the Kreyenhagen formation near Los Banos, from Locality A 3980 of the University of California Museum of Paleontology. The specimen figured in figure 1 could not be mounted successfully after drawing, but the other two figured specimens are deposited in the collections of the University of California Museum of Paleontology. The systematic classification is based on Haeckel's general system, with the emendations necessitated by the Code of Zoological Nomenclature.

Family SETHOPHORMIDIDAE

Tribe *Sethophormida* HAECKEL, 1882, Jenaische Zeitschr. f. Naturw., 15: 432; 1887, Chall. Repts., Zool., 18 (2): 1243.
Family *Anthocyrtida* HAECKEL, 1887, Chall. Repts., Zool., 18 (2): 1241–1242.
Family *Sethophormidae* HAECKEL. Frizzell and Middour, 1951, Bull. Univ. Missouri School of Mines and Metallurgy, Tech. Ser., 77: 29.

Dicyrtida multiradiata. Cyrtoidea with a two-jointed shell, divided by a transverse constriction into cephalis and thorax, and bearing numerous—four to nine or more—radial apophyses.

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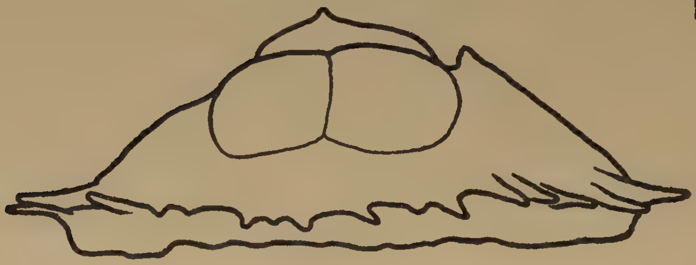
[1] Contribution from the Scripps Institution of Oceanography, New Series, No. 575.



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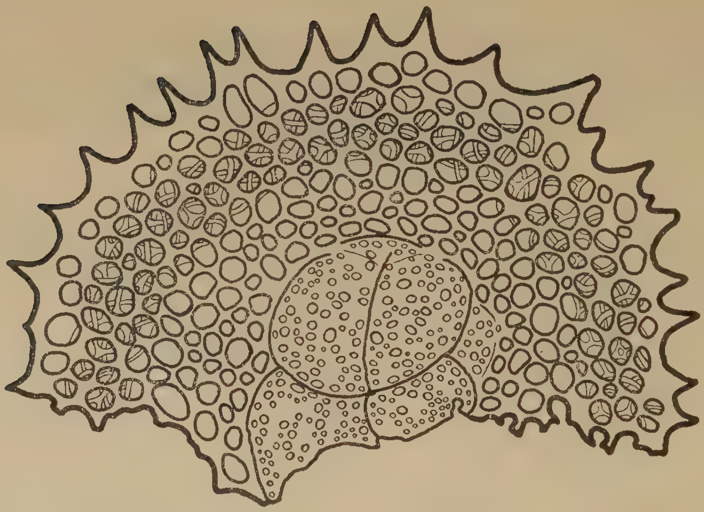

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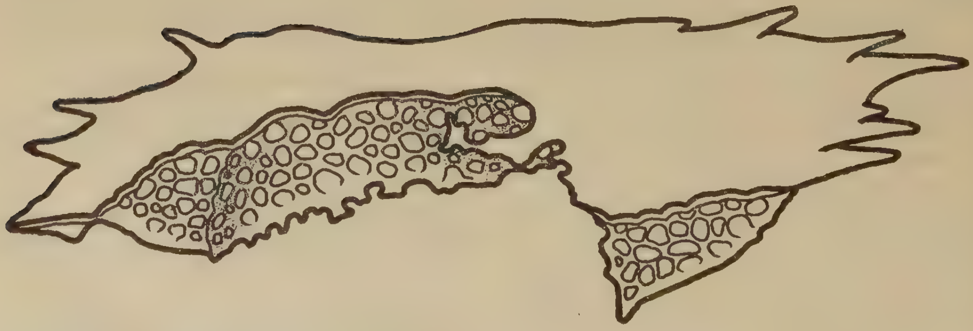

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FIG. *1*—Lateral view of a relatively small individual, showing the relations of the lobed cephalis, the expanded thorax, and the velum. Part of one of the cephalic lobes is broken away. ×330.

FIG. *2*—A broken test viewed from above, illustrating the nature of the pores of the cephalis and thorax. ×330.

FIG. *3*—Part of the thorax and velum, viewed laterally. ×330.

The family name is here emended to its correct derivation from the Greek genitive.

Subfamily SETHOPHORMIDINAE

Sethophormida HAECKEL (in part), 1882, Jenaische Zeitschr. f. Naturw., 15: 432; 1887, Chall. Repts., Zool., 18 (2): 1243.
Sethophorminae HAECKEL. Clark and Campbell, 1942, Geol. Soc. Amer., Sp. Pap., 39: 72.

Sethophormididae with the basal mouth of the shell open.

The subfamily name is here emended to its derivation from the Greek genitive.

Genus VELICUCULLUS Riedel and Campbell, n. gen.

Sethophormidinae with a spongy or lamellar velum on the oral surface of the broadly campanulate or almost discoidal thorax. Cephalis of several lobes.

Type species.—*Soreuma magnificum* Clark and Campbell, 1942.

This genus differs from all others of the subfamily in having a velum, which is quite a different structure from the separate peristome found in *Anthocyrtidium.* The peristome of *Anthocyrtidium* is probably homologous with the spine-bearing edge of this new genus.

VELICUCULLUS MAGNIFICUS (Clark and Campbell, 1942)

Soreuma (*Soreumium ?*) *magnificum* CLARK and CAMPBELL, 1942, Geol. Soc. Amer., Sp. Pap., 39: 51–52, pl. 4, fig. 15.
Soreuma (*Soreumidium*) *magnificum* CLARK and CAMPBELL. Clark and Campbell, 1945, Geol. Soc. Amer., Mem. 10: 28, pl. 5, fig. 2.

Campanulate shell greatly flattened, almost discoidal, especially as the cephalis is lost from most specimens. Cephalis delicate, with usually three or four lobes separated by distinct sulci, and 150–200 small circular pores scattered over the surface. Thorax greatly expanded, almost flat, with slightly rough surface: pores subcircular, as broad, to three times as broad, as the intervening bars, 6–10 in a vertical series, 22–27 on the half-circumference, arranged in indefinite vertical series, decreasing a little in size from the aperture towards the cephalic suture. 25–30 tooth-shaped radial apophyses on the margin of the thorax, not all exactly in one plane, generally extending almost horizontally. Occasionally, the bases of the larger radial apophyses are reticulated. Spongy velum on the lower surface of the thorax, extending inward from the bases of the radial apophyses, its width approximately 0.3 of the radius of the shell. Diameter of shell 300–350 μ, of thoracic pores 5–10 μ. Length of radial apophyses 50–30 μ. Width of cephalis 130–150 μ, its height 30–50 μ. Width of velum 35–50 μ.

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REPORT ON EXPERIMENTS DESIGNED TO DETERMINE EFFECTS OF UNDERWATER EXPLOSIONS ON FISH LIFE[1]

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[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 576. Submitted for publication March, 1952. In the conduct of the research and in the preparation of the article we have at times been carried out beyond our depth. We, therefore, very sincerely record thanks to those who have given us a helping hand. Encouragement, advice, and assistance have been furnished by many persons, including Frances N. Clark, Edward C. Greenhood, John E. Fitch, and others, of the California Department of Fish and Game; William W. Rand, of the Union Oil Company; Capt. Tom Crawford and crew, of that company's exploring ship, the SUBMAREX; R. A. Peterson, E. Pat Shultz, and Robert Day, of the United Geophysical Company; Louis N. Waterfall, consultant; Alfred B. Focke, of the United States Navy Electronics Laboratory; Carl H. Eckart, Russell W. Raitt, John D. Isaacs, Roger R. Revelle, Francis P. Shepard, Donald B. Sayner, Theodore R. Folsom, Conrad Limbaugh, and many others at the Scripps Institution of Oceanography.

INTRODUCTION

In the exploitation of major natural resources conflicts of values and interests often arise. Such a conflict arose when the oil industry, in its effort to meet the increasing demand for its product and to prepare for future needs, undertook seismographic exploration for untapped oil deposits in the rock layers beneath the coastal waters of Southern California. Such exploration requires a point source of intense low-frequency sound and the most practicable generating source is an explosion. Particularly effective and practicable, as explorations in the Gulf of Mexico have demonstrated, is the standard 60 percent gelatine dynamite, which produces a sharp shock wave with an abrupt front of great pressure intensity (Figure 8). Such a wave gives excellent results from the seismographic viewpoint. Unfortunately, however, this type of wave is very injurious to fishes that have an air-bladder, and most of the important food and game species possess this structure. Heavy mortalities of valued fishes resulted from the seismographic studies in the waters of Southern California (Aplin, 1947; Fitch and Young, 1948) and from tests made in Chesapeake Bay (Coker and Hollis, 1950). As a result of the fish killings in California the permits for submarine oil exploration were revoked in 1949, and were not renewed until September, 1951. The renewals were granted after the experiments recounted below had indicated it as probable that black powder would yield usable seismographic data without killing fish in disastrous numbers.

Research to determine the effects of underwater explosions on marine life has been limited. The effects of detonating explosives have received attention by Knight (1907), Gowanloch and McDougall (1944-1946), Aplin (1947), Indrambarya (1949), Gowanloch (1950), and Coker and Hollis (1950), as also in two reports (Anonymous, 1947 and 1948) on the cooperative researches in Chesapeake Bay. We have found no published data on the biological effects of underwater discharges of such relatively slow-burning explosives as black powder.

OBSERVATIONS ON THE EFFECTS OF LARGE CHARGES IN A RESTRICTED REGION

The first set of definite observations made by us to determine effects of underwater explosions on fishes was a by-product of geological experiments conducted by the Scripps Institution of Oceanography in cooperation with the United States Navy. Navy personnel did the firing. The primary object was to determine whether turbidity currents could be induced in submarine canyons by explosions set off at or near the head of the canyon. The tests were conducted in Scripps Submarine Canyon (Shepard, 1949, 1951a, b), immediately north of Scripps Institution, near La Jolla, California (Figure 1). The first trials were run on April 6 and 7, 1950, when ten 50-pound dynamite charges were set off, two near the sandy main head of the canyon at a depth of about 60 feet, two near the middle of this arm at a depth of about 250 feet, and six in the rocky main canyon, near its confluence with Sumner Branch, at depths of about 325 to 350 feet. Large fish kills resulted, but the collection was somewhat incomplete and selective (listed in first column of Table 1). Of the total recorded kill of 1,431 fish, 1,032 were blacksmith and 245 were rockfish of various species (for scientific names see list on page 366).

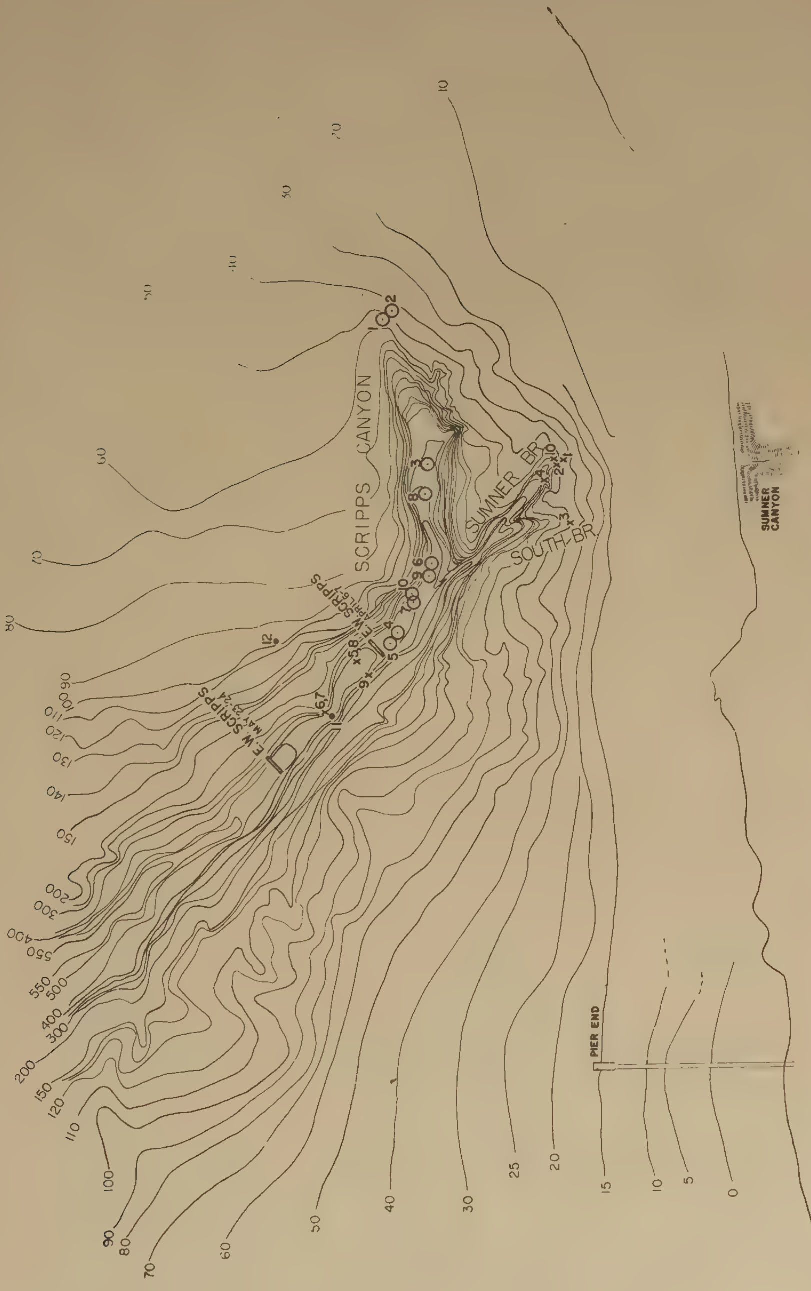
SCRIPPS CANYON
SUMMER BR
SOUTH BR
E.W. SCRIPPS
April 6-7
E.W. SCRIPPS
MAY 23-24
PIER END
SUMMER CANYON
0
5
10
15
20
25
30
40
50
60
70
80
90
100
110
120
130
140
150
200
300
400
500
550

FIGURE 1. Map of Scripps Submarine Canyon, showing location of dynamite explosions of April 6-7 (circles) and *May* 23-24 (crosses), 1950. **See Table 1. The pier is 1,000 feet long.** *Traced from map provided by Dr. Francis P. Shepard.*

TABLE 1

Record of Fish Collected Dead or Dying at Surface After Dynamite Explosions in Scripps Submarine Canyon, California

For scientific names see p. 366. This plus sign (+) indicates that additional specimens were destroyed but not recovered.

Date (1950)	Apr. 6-7	May 23							May 24			Totals	
												May 23	May 24
Blast No. (Figure 1)	----------	1	2	3	4	5	6–7	8	9	10–11	12–13	1–8	9–13
Depth (blast on bottom)	60–350	50	79	55	90	405	430	405	325±	60±	450± (&100)	50–405	60–450±
Time of blast (about)	1007–1619	0925	1030	1100	1310	1350	1440 1455	1555	1000	1030	1130	0925–1555	1000–1130
Weight of charge, pounds	50 or 100	50 or 100	50 or 100	50 or 100	100	50	50+50	100	100	50+50	50(+4)	50-100	50-100(+4)
Pacific sardine	--	--	--	1	--	--	--	2	--	--	--	3	--
Panama bristlemouth	1	--	--	--	--	--	--	--	--	--	--	--	--
Kelp bass	27	53	1	4	3	--	--	--	--	--	--	61	--
Sand bass	--	7	--	--	--	--	--	--	--	--	--	7	--
Grunion	29++	2	--	20	--	72	--	--	10	5	62+	94	77+
Jacksmelt	54+	21	8	12	29	7	--	3	--	--	7+	80	7+
Kelp topsmelt	--	1	--	--	--	9	1	15	--	--	5+	26	5+
Jack mackerel	--	--	--	1	--	--	--	--	--	--	--	1	--
Sargo	--	4	3	--	--	--	--	--	--	--	--	7	--
Ocean whitefish	3	--	--	--	--	--	--	--	--	--	--	--	--
Pink seaperch	16	--	--	--	--	1	--	6	--	--	8+*	7	8+*
Buttermouth seaperch	--	--	--	1	--	--	--	--	--	--	--	1	--
Sharpnose seaperch	3	--	--	--	--	--	--	1	1	--	--	1	1
Rubberlip seaperch	3	1	--	--	--	--	--	1	--	--	--	2	--
Pile perch	1	3	--	--	--	--	--	1	--	--	--	4	--
Blacksmith	1,032	1,978	334	289	39	--	--	47	--	4	2	2,687	6
Garibaldi	1	--	--	--	--	--	--	--	--	--	--	--	--
California sheepshead	3+	63	3	1	2	--	--	1	--	--	--	70	--
Opaleye	3	--	--	--	--	--	--	--	--	--	--	--	--
Bocaccio	4	--	--	12	--	--	--	--	--	--	1	12	1
Bass rockfish	30	--	2	13	--	--	--	1	--	--	--	16	--

Vermilion rockfish	15+	--	--	--	--	--	--	2	--	--	5*	2	--
Kelp rockfish	25	1	4	7	4	--	--	--	--	--	--	16	--
Widow rockfish	1	--	--	--	--	1	--	--	--	--	--	1	--
Spotted rockfish	83	--	3	1	1	--	--	192	1	--	--	197	1
Halfband rockfish	9	--	--	--	--	2	--	3	--	--	--	5	--
Speckled rockfish	46	--	--	--	1	--	--	2	--	--	4*	3	4*
Rosy rockfish	7	--	--	--	--	2	1	--	--	--	--	3	--
Greenspotted rockfish	7	--	--	--	--	3	--	3	--	--	1*	6	1*
Pink rockfish	10	--	--	--	--	15	6	2	--	--	1*	23	1*
Starry rockfish	3	--	--	--	--	3	2	1	--	--	2*	6	2*
Spanishflag	--	--	--	--	--	--	--	1	--	--	--	1	--
Striped rockfish	1	--	--	--	--	--	--	--	--	--	1*	--	1*
Brown rockfish	--	--	--	--	1	--	--	--	--	--	--	1	--
Whitebelly rockfish	2	--	--	--	--	--	--	--	1	--	--	--	1
Calico rockfish	1	--	--	--	--	--	--	--	--	--	--	--	--
Treefish	1	--	--	--	--	--	--	--	--	--	--	--	--
Rockfish (species?, very yg.)	--	--	--	--	--	--	2	--	--	--	--	2	--
Crested goby	--	--	1	7	--	--	--	--	--	--	--	8	--
Zebra goby	1	--	--	--	--	--	--	--	--	--	--	--	--
Northern midshipman	2	--	--	--	--	--	--	1	--	--	--	1	--
Spotted cusk-eel	7	--	--	--	--	2	--	1	--	--	--	3	--
Totals	1,431+	2,134	359	369	80	117	12	286	13	9	99+	3,357	121+

* Fish so marked, plus 50 to 100 additional pink seaperch that were not recovered, were presumably destroyed by the unscheduled blast northwest of the main explosions.

The local fish population presumably recovered between the operations of April 6-7 and May 23-24. The similarity between the lists of fishes destroyed on the two occasions (Table 1) is striking.

During the second operation, on May 23 and 24, an effort was made to tally all fish killed. Six 50- or 100-pound charges were set off, four on May 23 and two, close together, on May 24, near the sandy heads of South Branch and Sumner Branch, in depths of 50 to 90 feet; and six were discharged in the rocky main canyon, at depths of about 325 to 450 feet, four on May 23 and two on May 24; in addition, one unscheduled 4-pound charge was exploded on May 24, above the northwestern wall of the main canyon. The two sets of explosions were discharged to either side of the area blasted on April 6 and 7. In view of the large radius of kill observed, however, it is assumed that the canyon was affected not only near each set of shots but also through much of the intervening area. Due to the extreme narrowness and straight alignment of the rock-walled canyon, it may be assumed that the effects of the explosions were intensified up and down the trench.

The very extensive kill on the first day (May 23) was probably almost complete for the regions affected. Approximately duplicated shots of the second day yielded only 121 fish. Of these, 89, or 74 percent, were silversides (Atherinidae), free-swimming fish whose numbers were presumably unaffected by the explosions of the previous day. Of the 32 remaining fish, 22 (marked with an asterisk in Table 1) were almost certainly killed above the northwestern canyon wall or on the canyon edge, for they appeared well north of the others and later, presumably as the result of the unscheduled 4-pound shot set off in that region near the surface. Eliminating these two sets of specimens, only 10 fish were taken as a result of the four shots of the second day, where 3,357 were picked up following the eight shots on the first day. It seems possible that most of the fish population was destroyed through perhaps 1,000 or 1,500 feet of the upper part of the submarine canyon. The destructiveness of large dynamite charges may be very extensive.

In the four successive shallow-water shots of May 23 there was a marked decrease in the kill, particularly in the series (1, 2, and 4) at the head of Sumner Branch (Table 1 and Figure 1). Had the fish merely moved down into the main Scripps Canyon, more would likely have been killed by the subsequent charges (6-8) in deeper water. The rather high mortality from blast 8, contrasting with the lesser kill of blast 5, discharged about two hours earlier at the same location, may have resulted from a down-canyon movement of the fish between the two shots.

It is obvious that the bottom fish did not move into the canyon overnight, between the days in May when the explosions were set off, either from possible refuges in the steep-walled tributaries or from more distant habitats. There is reason to believe, however, that the population was again restored within a few months. In extensive diving operations with self-contained units Conrad Limbaugh and other students found during 1951 that fish again abounded in the canyon, in the general region where the fish life had been largely eliminated on May 23-24, 1950. Here at depths of 35 to 185 feet Limbaugh observed 31 species of fish (for scientific names see list p. 366). The blacksmith, again the most abundant fish, was observed in particularly large concentrations at the heads of canyons and at the junctions of the tributaries. Various species of rockfish were seen in considerable numbers along the rim of the canyon below 100 feet and at the canyon junctions. At depths of 50 to 100 feet, along the rim, kelp bass and ocean-whitefish were observed at times in large schools. Several seaperches (Embiotocinae) were occasionally found in large numbers at depths of 35 to 60 feet. At times large schools of señoritas were seen at depths less than 50 feet. In general, in 1951, fish were apparently more numerous in and over the canyon than in any comparable near-by area. The fish life of the canyon, which is often favored by local anglers, had seemingly become restored.

1951 EXPERIMENTS

In 1951 experiments were conducted for the specific purpose of determining whether methods applicable to seismographic exploration for oil might be found that would cause no considerable fish mortality. These trials were conducted by the Union Oil Company of California on the exploring ship Submarex, under a permit granted by the California Department (then Division) of Fish and Game on March 2, 1951 (later amended). The operations were restricted in several ways and the permit specified that the experiments would be a joint enterprise of the oil company and the Scripps Institution of Oceanography of the University of California. A preliminary report was prepared in May, 1951, for the use of the State Fish and Game Commission and of other parties particularly concerned. It serves as the main basis for this presentation.

At the outset of these experiments the object was to determine whether small charges of dynamite jetted into the bottom (Figure 2) might be exploded without causing serious harm to the fish life in the overlying water. It was determined, however, that fish confined in experimental cages and others, free-swimming, were seriously affected. After repeated trials failed to indicate that small jetted charges of either dynamite or Hercomite would be inoccuous, experiments were undertaken with explosives (Hercules FFG and FFFG black powders) having lower peak intensities and lower frequencies.

The black powder charges were first jetted into the bottom, but when it appeared that the bubble pulse produced by such powder when jetted as deep as 40 feet might interfere with the geophysical analysis, the project was expanded (by extension of the permit) to include trials with the charge lying on the bottom and with the charge hung a few feet below the surface.

The experiments were observed by Edward Greenhood, representing the Department of Fish and Game, as well as by the Scripps representative (Rechnitzer) and the Union Oil Company's geologist (William W. Rand). On several occasions other officials of the Scripps Institution and of the California State Fisheries Laboratory observed the trials and on one day Messrs. DeWitt, Harrison, and Woods, representing the Ocean Fish Protective Association, were aboard. The stipulations of the permit (as amended) were rigidly adhered to and every facility was provided for the conduct of the experiments and for the observation and recording of the results. A boat with crew (Figure 4) was made available to the observers. The boat stood by in readiness for each shot, in order to pick up any marine life that might be killed or injured by the blast. All information regarding the methods involved in carrying out the experiments

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3

4

5

and all information gathered from them were made available to the observers.

The work was started off Silver Strand, which separates San Diego Bay from the ocean. Explosions 6, 9–13, and 16, as seriated in Tables 2–4, were set off here. The next test (25) was made just north of La Jolla. The work was then transferred to the vicinity of the Orange–Los Angeles county line, after sedimentary overburden of adequate depth for the jetted tests could not be located off San Diego County.

In each set of experiments an effort was made to keep as nearly uniform as possible all varying factors other than size and position of the charge.

Materials and Methods

Fishes

Seven species of fish, marked by an asterisk in the list on page 366 were used in the experimental cages. Some individuals of each kind were killed in cages by the dynamite charges. Four of these species and seven others were killed by dynamite while free-swimming. These are marked by a dagger (†). In the two Hercomite trials anchovies and one queenfish were killed. In the black powder experiments only the anchovy was killed in cages and one Pacific mackerel was the only fish killed while free-swimming.

The number of species used in the experiments was limited because few kinds were readily available. Anchovies were frequently the only kind obtainable; jack mackerel, kingfish, sardine, queenfish, pompano, and grunion made up a very small percentage of any single purchase. In the San Diego area fish were taken when available, either from holding receivers or directly from the fishing boat. In the San Pedro area fish were purchased daily from local bait dealers at approximately 7.30 a.m., within eight hours after capture. The specimens were taken directly from their holding tanks. Therefore, the fish, after transfer to the holding tank on the research vessel, had been handled only twice by dipnets and were taken from the ocean as recently as was practicable. None were held over from the operations of the previous day. The kingfish were mostly taken by hook and line. They were seemingly sound when placed in the cages. In general, the fish were in excellent condition and were considered to be suitable experimental material.

The fish were held in a 4′ × 4′ × 4′ wooden commercial-type bait tank, through which at all times an adequate flow of fresh sea water was maintained by an air-free pump. The tank was placed on board where the fish when dip-netted out of the tank could be transferred rapidly in a bucket to the live cages (Figure 5). All fish kept well throughout the experiments. Fatalities due to handling were negligible. It was found by experiment that internal injuries, such as those produced by a blast, could be simulated only by extraordinarily rough treatment.

←

FIGURE 2. Jetting a charge into the ocean floor. *Photograph by William W. Rand, April, 1951.*
FIGURE 3. Loading position of the nine-cage unit. *Photograph by William W. Rand, April, 1951.*
FIGURE 4. Motor launch scouting for possible free kill. *Photograph by William W. Rand, April, 1951.*
FIGURE 5. Loading fish into a bottom cage. *Photograph by William W. Rand, April, 1951.*

Cages

In order to avoid possible absorption of shock-wave energy by such air-containing material as twine netting and wooden frames, all cages were constructed of ¼-inch mesh galvanized hardware cloth laid over a welded frame of ⅜-inch steel rod (Figure 6). They were similar to those used in previous investigations (Aplin, 1947; Anonymous, 1948). The dimensions of each were 18″ × 36″ × 36″. A door 18″ × 18″ was placed on one 18″ × 36″ side. Usually only two cages were used in each experiment, one near the surface and one on the bottom. In some experiments, nine cages were secured five feet apart, both vertically and horizontally, by an agle-iron frame (Figure 7). The nine-cage unit was held in an upright position by four buoys. To this unit an extra buoyed surface cage was attached.

Control cages, one at the surface and one on the bottom, were placed in a few experiments 100 to 200 feet from the shot. None of the fish in the controls showed any damage attributable to the blast.

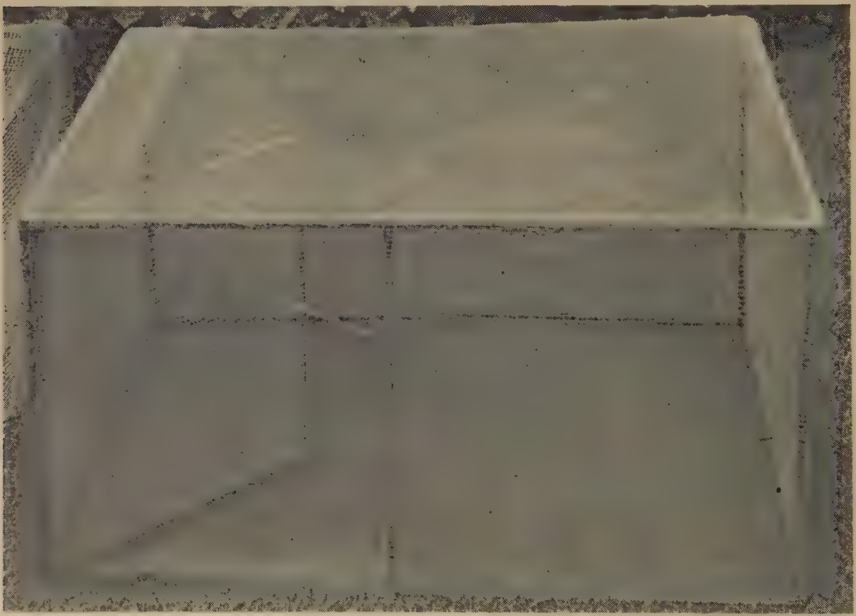

FIGURE 6. All-metal holding cage (18″ x 36″ x 36″). *Photograph by William W. Rand, April, 1951.*

Handling of Cages

The cages were submerged on edge to a depth of 18 or more inches alongside a launch that was tied to the research vessel (Figure 5). The launch permitted the operating crew to work at water level. The fish were gently poured from the bucket into the live cage. When the door was secured the cage was completely submerged. Once in the water, the cage righted itself, due to the bridling, so that the fish were limited in vertical movement to 18 inches. The cages were then placed in position for the firing of the charge. Loading time for each cage was about one minute.

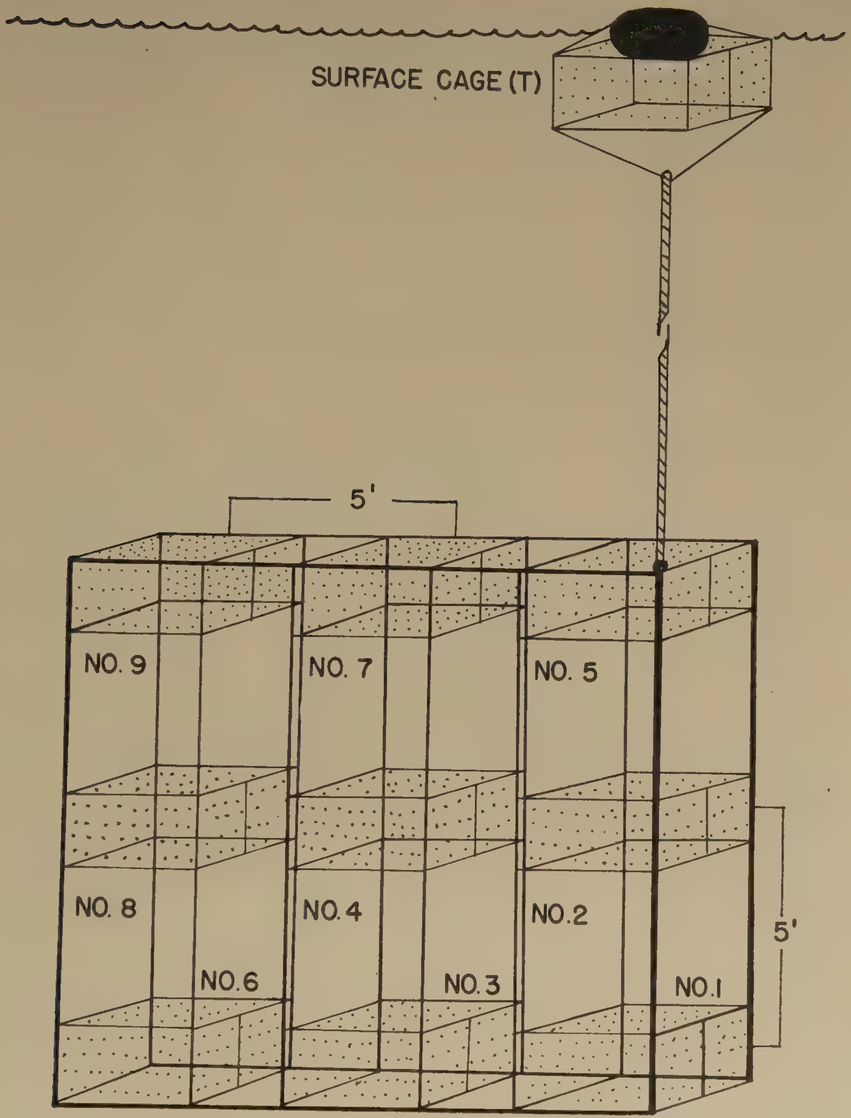

FIGURE 7. Nine-cage unit. No. 1 cage oriented nearest to jet hole.

The nine-cage unit, suspended from a boom, was loaded as it was held at 90 degrees from its final position, so that the door of each cage was up (Figure 3). When a row of three cages had been loaded, as described above, the unit was lowered so that the next row could be similarly filled. On completion of the loading, which required about 15 minutes, the cage was turned to its original position with a 36″ × 36″ side up.

A recording instrument was attached to the top of one of the cages, which was placed as nearly vertically over the shot as was feasible. The specific cage from the bottom is indicated in Tables 2–4. The recording device measured the peak intensity of the shock wave (Figures 8–9, which is recorded in p.s.i. (pounds per square inch). It is assumed, in general, that the fish in a particular cage were subjected, approximately, to the pressure indicated by the instrument attached to that cage, but in some experiments (as in Exp. 19), the fish were probably subject to less pressure because they were in the shadow zone (p. 362). It would have been better to have placed the instrument in the center of the cage, as was done in the Chesapeake Bay experiments (Anonymous, 1947, 1948).

When the charges were jetted, a crew member standing on the research vessel placed the nearest bottom cage (No. 1) as close to the jet hole as he could. He set the cages free when they were aligned with the shot wire leading to the jetted charge. Precise placement of the No. 1 cage proved difficult, particularly in deep water. The actual distance between charge and cage (''Hydrophone Dist.'' in Tables 2–4) was computed whenever the hydrophone was attached to a cage. The lower cage normally rested on the bottom and was equipped with a grapple to restrict its movement during the experiment. The paired cages were secured together by a line. The upper cage, supported by a steel buoy, floated just beneath the surface.

In those experiments (1, 40-44, 46, 50; Tables 2, 4), in which the explosive was floated either two or four feet beneath the surface, the upper cage floated just beneath the surface, but was held off to the side of the explosion rather than approximately over the blast. This was accomplished by a line 20 feet long, which was kept taut by another line running to the research vessel. The lower cage was suspended in mid-water either 40 feet below the charge or 40 feet below the surface cage.

In four experiments (51, 52, 60, 61) the bottom cage was separated either 5 or 10 feet from the charge by a metal rod and the recording instrument was attached to this cage.

Within about 10 or 15 minutes, after all the equipment was set in place, the ship was moved approximately 100 feet from the site of the blast. Immediately after the firing the launch was run to the site of the shot, in order to make prompt observations of caged fish and of whatever free marine life might surface.

As soon as it was evident that no free-swimming fish were damaged or that all that were going to surface had already done so, the cages were pulled aboard the launch and the fish were removed for dissection, analysis, and preservation. Controls indicated that it was unnecessary to leave fish in cages for any prolonged period, as dissection reveals the damage. It is believed that the damage is produced almost momentarily by the blast. All fish subjected to experiments involving black powder were dissected immediately on board the research vessel and were then preserved.

Handling of Charges

A standard factory-prepared charge of five pounds of 60 percent strength dynamite was used. Smaller charges were prepared from sections of a five-pound stick. Larger charges were formed by binding five-pound units together.

Initially a quantity of Hercules FFG or FFFG powder was weighed out on a spring balance and placed in a piece of automobile radiator hose. Subsequent charges of approximately the same weight were prepared by filling sections of hose of equal length with powder. Charges exceeding 20 pounds, with the exception of the 40-pound charge in Experiment 45, were packed in two types of containers, which gave different results. The 45-pound charges were placed either in five-gallon shark-liver cans (each holding approximately 45 pounds, as determined by R. A. Peterson, of United Geophysical Company), or in two sheet-metal tubes, which were bound together to make a charge of about 40 pounds. Each tube was approximately five inches in diameter and twenty-five inches long. One detonator was placed in each tube and one in each five-gallon tin. The charge sizes as recorded in the table were obtained from William W. Rand.

Pressure Measurements

The pressures, recorded in pounds per square inch (Tables 2–4), were calculated by and obtained from E. Pat Shultz and Robert Day of the United Geophysical Company. The measurements were made with an underwater piezoelectric (tourmaline) gauge of type B (as illustrated by Cole, 1948, Fig. 5.11). Shultz reports (in letter) that ''much of our technique followed the methods of Cole, and we used the well-known ''Q-Step'' system of calibration described by him on page 192, together with gauge constants supplied by the makers (Cambridge Thermionic Corp.) and independently checked by us with measurements of explosives (TNT) of standardized strength.''

Permanent records were obtained by photographing the screen of a cathode-ray oscilloscope. Sample records for dynamite and black powder explosions illustrate a fundamental difference (Figures 8–9). The dynamite explosion record shows the sharp, violent nature and abrupt front of the pressure peak, as contrasted with the slow development of peak pressure of small amplitude from a black powder explosion.

During these trials it was found by Shultz that, when plotted on a log-log scale, the peak pressure near the bottom from jetted five-pound dynamite charges bore a linear relationship (Figure 10) to the distance from the explosion (the ''Hydrophone Dist.'') and the pressure decreased inversely as the 2.6 power of the distance, rather than the approximately 1.15 power usually reported for sea water.

Miscellaneous Data

Locality of each operation was obtained from the captain of the research vessel. Water depths were read directly from a Bludworth fathometer which signals in both fathoms and feet. Bottom samples were obtained from the jetting apparatus; in some experiments, also by diving. Rechnitzer and Limbaugh occasionally dove with self-contained diving apparatus in an attempt to determine effects that were not visible at the surface.

Criteria for Damage

To stay on the safe side from the standpoint of the conservation and utilization of the fishery resources, rigid criteria were adopted for estimating the damage done to fish. Any apparent injury not definitely

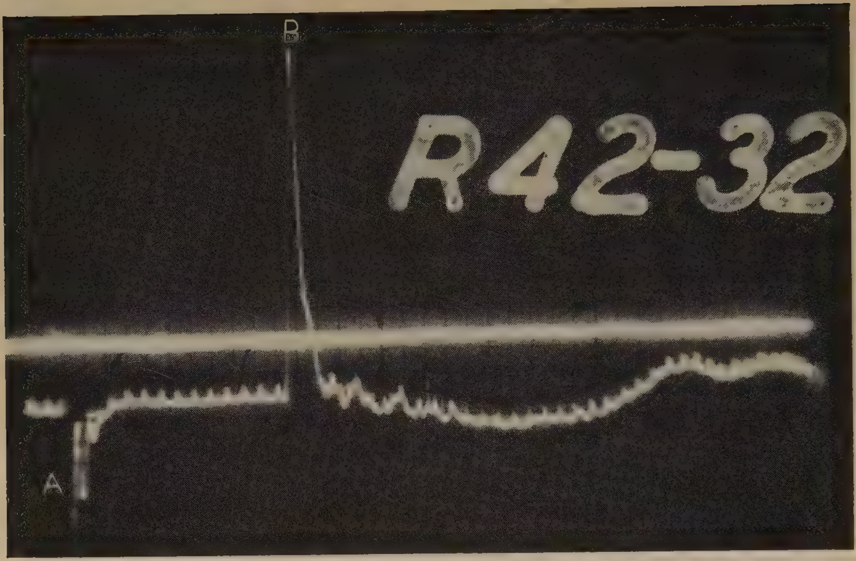

FIGURE 8. Oscillogram of 5-lb. dynamite explosion No. 19. (A) Charge fired. (B) Peak pressure, 83 p.s.i. The distance from (A) to the base of peak (B) measures the time required for the shock to travel from the explosion to the hydrophone. The distances between the small peaks represent milliseconds. *Photograph by E. Pat Shultz and Robert Day, April, 1951.*

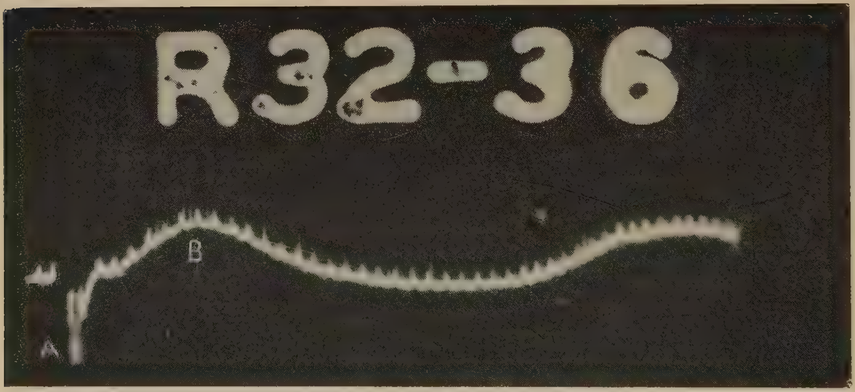

FIGURE 9. Oscillogram of 5-lb. black-powder explosion No. 65. Peak pressure (B), 6.8 p.s.i. *Photograph by E. Pat Shultz and Robert Day, April, 1951.*

attributable to handling or to other causes than that of the explosion was interpreted as an indication of probable death due to the blast. It is thought highly probable that most fish seriously injured by a blast would succumb later, through weakness, disease, or predation. Under favorable conditions, however, some and perhaps many of the affected fish, particularly those that are only temporarily stunned, probably recover and survive without permanent harm. The criteria, therefore, may have been too rigid. Further research is indicated.

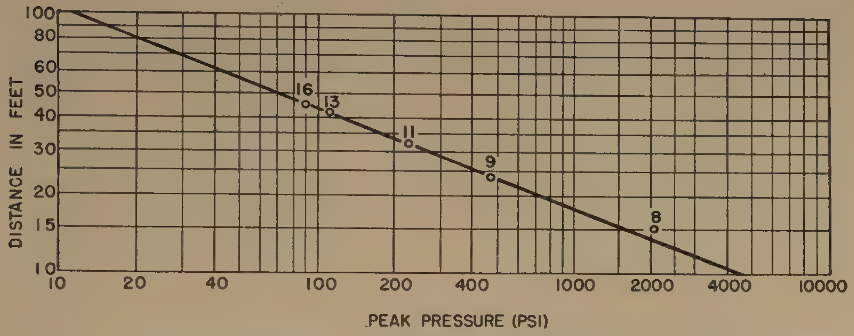

FIGURE 10. The decay with distance of the pressure from 5-lb. dynamite charges (decreasing inversely as the 2.6 power of the distance). *Redrawn from graph prepared by E. Pat Shultz.*

Internal damage, as determined by dissection, involved: (1) any hemorrhaging obviously not due to dissection, regardless of whether or not the cause of the bleeding was determined; (2) any break in the viscera or peritoneum; (3) a burst air-bladder; (4) a ruptured kidney; (5) gonad damage, or milt or eggs free in the abdominal cavity. Usually but not always any one of these symptoms was accompanied by several others, but in some tests only one was apparent.

Controls indicated that hemorrhaging in the muzzle and eyes of anchovies was due to confinement in the cages.

Results

Sharply contrasting results were obtained with dynamite (Table 2) and black powder (Table 4). Some comparative data were secured with Hercomite (Table 3).

The largest dynamite charges used in these experiments (10 pounds) do not compare with those that were often employed in the earlier seismographic studies nor with those utilized in the submarine-canyon studies reported above. Fish kills, nevertheless, resulted.

Ten-pound Charges of 60 Percent Dynamite

Whether exploded just below the surface (Exp. 1) or jetted 50 to 55 feet into the bottom sediment (Exps. 2–3), the 10-pound charges proved fatal to fish. The surface explosion, as would be expected from previous operations, killed fish (8 sauries). It was set off without the use of caged fish, to determine whether fish were present where they were not being killed by black powder. Both jetted blasts killed caged fish. One explosion destroyed caged fish from surface to bottom. The other blast, with somewhat lower indicated peak intensity, killed fish in the surface cage but not in the bottom container; in addition it destroyed two free-swimming fish.

Five-pound Jetted Dynamite Charges

The 19 experiments (Nos. 4–22) performed with a five-pound jetted charge of 60 percent dynamite also indicated fatal results. This charge was used most frequently for three reasons: (1) it was thought to be desirable from a seismographic viewpoint; (2) this size of charge was most conveniently handled in the jetting operation; and (3) it was desired to have an experimental standard.

TABLE 2

Data on Effects of Underwater Explosions With 60 Percent Dynamite

The experiments are here numbered in sequence from more lethal to less lethal results, without reference to the sequence in which the trials were run. Controls are marked "Contr." in place of the pounds of the charge. Under "Location," "down" means below surface, "Bott." indicates that the charge lay on the bottom, and "J." stands for jetted. Under "Hydrophone Loc." (location), "Surf." and "Bott." respectively indicate attachment to surface cage or to bottom cage. The "Nos." in this column and under "Cage Loc." (location) refer to the cage numbers in the multiple-cage trials (Figure 7). "Hydrophone Dist." (distance) from charge was computed from the seismographic record. Full vernacular names and the scientific names are given on p. 366. Under "Free Fish Killed" the total kill of uncaged fish is estimated, including fish seen to be eaten by gulls and those seen swimming with greatly disturbed equilibrium.

Exp.	Lbs.	Location	Hydrophone		Peak p.s.i.	Water depth, feet	Cage loc.	Fish species	Fish in cages		Free fish killed
			Loc.	Dist., feet					Unharmed	Killed	
1	10	4′ down	--	--	--	100	None	Saury	--	--	8
2	10	J. 50′	Surf	82	82	29	Surf.	Sardine	0	1	0
								Anchovy	0	8	0
								Jack mackerel	0	2	0
								Pompano	0	1	0
							Bott.	Sardine	2	0	0
								Anchovy	6	0	0
								Jack mackerel	2	0	0
							--	Kingfish	--	--	2
3	10	J. 55′	No. 5	52	148	30	Surf.	Anchovy	0	18	0
							No. 1	Anchovy	7	0	0
							No. 2	Anchovy	0	10	0
							No. 3	Anchovy	10	4	0
							No. 4	Anchovy	8	5	0
							No. 5	Anchovy	0	16	0
							No. 6	Anchovy	7	7	0
							No. 7	Anchovy	0	13	0
							No. 8	Anchovy	0	16	0
							No. 9	Anchovy	0	6	0
3	Contr.						Surf.	Anchovy	10	0	0
							Bott.	Anchovy	11	0	0

4	5	J. 5′	--	--	--	27	None	Queenfish	--	--	4
								Kingfish	--	--	3
5	5	J. 7′	Bott.	61	163	22	None	Jacksmelt	--	--	8
								White seaperch	--	--	2
6	5	J. 15′	Bott.	--	403	56	Surf.	Anchovy	0	6	0
							Bott.	Anchovy	0	3	0
							--	Jacksmelt	--	--	200
7	5	J. 15′	Surf.	49	176	30	Surf.	Anchovy	0	9	0
							Bott.	Anchovy	0	12	0
							--	Jacksmelt	--	--	20
8	5	J. 15–18′	No. 2	22	1,343	30	Surf.	Anchovy	0	3	0
							Nos. 1–9	Anchovy	0	51	0
							--	Jacksmelt	--	--	80
							--	White seaperch	--	--	1
8	Contr.						Surf.	White seaperch	14	0	0
							Bott.	White seaperch	6	0	0
9	5	J. 25′	Bott.	24	468	56	Surf.	Anchovy	0	6	0
							Bott.	Anchovy	0	2	0
							--	Jacksmelt	--	--	200
							--	Grunion	--	--	2
10	5	J. 30′	Bott.	29	501	56	Surf.	Anchovy	4[1]	0	0
							Bott.	Anchovy	4[1]	0	0
11	5	J. 32′	Bott.	32	225	56	Surf.	Anchovy	0	3	0
							Bott.	Anchovy	0	3	0
							--	Pacific mackerel	--	--	1
							--	Kingfish	--	--	4
12	5	J. 35′	Bott.	43	89	82	Surf.	Anchovy	0	6	0
							Bott.	Anchovy	6	0	0
12	Contr.						Surf.	Anchovy	11	0	0

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[1] These fish, in five of the earlier experiments, were not dissected and might have had internal injuries, which later would have been regarded as indicative of probable death.

TABLE 2—Continued

Data on Effects of Underwater Explosions With 60 Percent Dynamite

Exp.	Lbs.	Location	Hydrophone		Peak p.s.i.	Water depth, feet	Cage loc.	Fish species	Fish in cages		Free fish killed
			Loc.	Dist., feet					Unharmed	Killed	
13	5	J. 35–40′	Bott.	42	111	56	Surf.	Queenfish	1[1]	0	0
								Kingfish	1[1]	0	1
							Bott.	Kingfish	2[1]	0	--
14	5	J. 40′	Bott.	50	110	78	Surf.	Anchovy	10	0	0
								Jack mackerel	3	0	0
								Kingfish	3	2	0
							Bott.	Anchovy	6	0	0
								Jack mackerel	2	0	0
								Kingfish	5	0	0
15	5	J. 40′	No. 5	44	106	30	Surf.	Anchovy	10[1]	0	0
							Nos. 1–9	Anchovy	57[1]	0	0
15	Contr.						Surf.	Anchovy	3[1]	0	0
							Bott.	Anchovy	7[1]	0	0
16	5	J. 40′	Bott.	45	90	82	Surf.	Anchovy	6[1]	0	0
							Bott.	Anchovy	4[1]	0	0
17	5	J. 40′	Surf.	--	43	26	Surf.	Anchovy	5	3	0
								Jack mackerel	1	2	0
								Kingfish	0	2	1
							Bott.	Anchovy	7	0	0
								Kingfish	0	1	--
							--	Shiner seaperch	--	--	1
17	Contr.						Surf.	Sardine	2	0	0
								Anchovy	4	0	0
								Jack mackerel	1	0	0
							Bott.	Anchovy	5	0	0
								Jack mackerel	3	0	0
18	5	J. 45′	--	--	--	30	Surf.	Anchovy	0	10	0
							Bott.	Anchovy	0	6	0
							--	Kingfish	--	--	1

19	5	J. 45′	Bott.	65	83	92	Surf.	Anchovy	4	2	0
							Bott.	Anchovy	6	0	0
20	5	J. 50′	Bott.	--	106	30	Surf.	Sardine	2[1]	0	0
								Anchovy	3[1]	0	0
								Jack mackerel	4[1]	0	0
							Bott.	Sardine	3[1]	0	0
								Anchovy	1[1]	0	0
								Jack mackerel	1[1]	0	0
20	Contr.						Surf.	Sardine	2	0	0
								Anchovy	4	0	0
								Jack mackerel	1	0	0
							Bott.	Anchovy	5	0	0
								Jack mackerel	3	0	0
21	5	J. 50′	No. 5	67	76	30	Nos. 1–9	Anchovy	83	0	0
							1–2, 4–9	Jack mackerel	11	0	0
22	5	J. 65′	No. 5	--	--	30	Surf.	Anchovy	0	9	0
							Bott.	Anchovy	0	5	0
23	2½	J. 15′	Surf.		125	30	Surf.	Anchovy	0	7	0
							Bott.	Anchovy	5	2	0
24	2½	J. 15′	Surf.	75	50	30	Surf.	Anchovy	4	0	0
							Bott.	Anchovy	7	3	0
25	2½	J. 35–40′	Bott.	--	162	56	Surf.	Anchovy	0	8	0
							Bott.	Anchovy	7	2	0
							--	Jack mackerel	--	--	340
							--	Pacific mackerel	--	--	1
							--	Slim midshipman	--	--	1
							--	Pipefish	--	--	1
26	1¼	J. 10′	Surf.	34	186	28	Surf.	Anchovy	0	6	0
							Bott.	Anchovy	0	7	0
							--	Jacksmelt	--	--	5
27	1¼	J. 10′	--	--	--	30	None	Jacksmelt	--	--	1
								White seaperch	--	--	1

[1] These fish, in five of the earlier experiments, were not dissected and might have had internal injuries, which later would have been regarded as indicative of probable death.

TABLE 2—Continued

Data on Effects of Underwater Explosions With 60 Percent Dynamite

Exp.	Lbs.	Location	Hydrophone		Peak p.s.i.	Water depth, feet	Cage loc.	Fish species	Fish in cages		Free fish killed
			Loc.	Dist., feet					Unharmed	Killed	
28	1¼	J. 15′	No. 5	20	296	30	Nos. 1–3, 5–9	Anchovy	7	38	0
							No. 4	Anchovy	0	6	0
								Grunion	0	1	0
29	1¼	J. 15′	Surf.	43	117	30	Surf.	Anchovy	0	5	0
								Grunion	0	2	0
30	1¼	J. 15′	Bott.	52	30	30	None	--	--	--	0
31	1¼	J. 15′	Bott.	54	24	30	Surf.	Anchovy	6	0	0
32	1¼	J. 25′	Surf.	60	73	29	Surf.	Anchovy	0	4	0
								Grunion	0	2	0
							Bott.	Anchovy	0	5	0
33	1¼	J. 30′	Bott.	26	128	29	Surf.	Anchovy	2	7	0
								Grunion	0	1	0
							Bott.	Anchovy	3	4	0
34	1¼	J. 30′	Surf.	65	54	29	Surf.	Anchovy	6	0	0
								Grunion	2	0	0
							Bott.	Anchovy	8	0	0
35	1¼	J. 30′	Surf.	68	50	29	Surf.	Anchovy	4	2	0
								Grunion	0	2	0
							Bott.	Anchovy	5	0	0
36	1¼	J. 30′	Surf.	65	45	29	Surf.	Anchovy	6	0	0
								Grunion	1	0	0
							Bott.	Anchovy	10	0	0

TABLE 3

Data on Effects of Underwater Explosions With Hercomite

For abbreviations see sublegend to Table 2

Exp.	Lbs.	Location	Hydrophone		Peak p.s.i.	Water depth, feet	Cage loc.	Fish species	Fish in cages		Free fish killed
			Loc.	Dist., feet					Unharmed	Killed	
37	4	J. 20′	Bott.	17	193	30	Surf.	Anchovy	0	9	0
							Bott.	Anchovy	0	5	0
								Queenfish	0	1	0
38	4	J. 30′	Bott.	29	138	30	Surf.	Anchovy	0	12	0
							Bott.	Anchovy	0	9	0
38	Contr.						Surf.	Anchovy	4	0	0
							Bott.	Anchovy	4	0	0
39	Contr.					30	Surf.	Anchovy	5	0	0
							Bott.	Anchovy	6	0	0

TABLE 4

Data on Effects of Underwater Explosions With FFG and FFFG Black Powder

For abbreviations see sublegend to Table 2

Exp.	Lbs.	Location	Hydrophone		Peak p.s.i.	Water depth, feet	Cage loc.	Fish species	Fish in cages		Free fish killed
			Loc.	Dist., feet					Unharmed	Killed	
40	45	4′ down	Bott.	43	160	100	Surf.	Anchovy	10	0	0
							Bott.	Anchovy	5	0	0
								Pompano	1	0	0
							----	Pacific mackerel	--	--	1
41	45	4′ down	Bott.	39	124	100	Surf.	Anchovy	11	0	0
							Bott.	Anchovy	9	0	0
42	45	4′ down	Bott.	23	--	100	Surf.	Anchovy	9	0	0
43	40	4′ down	Bott.	61	--	100	Surf.	Anchovy	1	6	0
							Bott.	Anchovy	8	0	0
44	40	4′ down	Bott.	56	--	100	Surf.	Anchovy	1	8	0
							Bott.	Anchovy	7	0	0
45	40	J. 10′	Bott.	37	41	30	Surf.	Anchovy	12	0	0
							Bott.	Anchovy	12	0	0
46	20	4′ down	Surf.	21	20	100	None	--	--	--	0
47	20	J. 10′	--	--	--	30	Surf.	Anchovy	4	0	0
								Queenfish	1	0	0
							Bott.	Anchovy	8	0	0
48	20	J. 10′	Bott.	17	48	30	Surf.	Anchovy	8	0	0
							Bott.	Anchovy	6	0	0
49	20	J. 10′	Bott.	14	58	30	Surf.	Anchovy	10	0	0
							Bott.	Anchovy	8	0	0
50	10	2′ down	Bott.	23	--	100	Surf.	Anchovy	10	0	0
								Grunion	1	0	0
51	10	Bott.	Bott.	14	--	30	Surf.	Anchovy	5	2	0
							Bott.	Anchovy	1	4	0
52	10	Bott.	Bott.	21	--	30	Surf.	Anchovy	6	0	0
							Bott.	Anchovy	7	0	0
53	10	J. 5′	--	--	--	30	Surf.	Anchovy	6	0	0
							Bott.	Anchovy	7	0	0
54	10	J. 5′	--	--	--	30	Surf.	Anchovy	6	0	0
							Bott.	Anchovy	2	0	0
55	10	J. 10′	Bott.	20	10.8	30	Surf.	Anchovy	7	0	0
								Jack mackerel	2	0	0
							Bott.	Anchovy	7	0	

56	10	J. 10′	Bott.	13	10	30	Surf.	Anchovy	4	0	0
								Kingfish	2	0	0
							Bott.	Anchovy	5	0	0
								Jack mackerel	1	0	0
								Kingfish	2	0	0
57	9	J. 20′	Bott.	73	4.0	92	Surf.	Anchovy	8	0	0
							Bott.	Anchovy	5	0	0
58	9	J. 20′	Bott.	27	11	92	Surf.	Anchovy	8	0	0
							Bott.	Anchovy	10	0	0
59	9	J. 20′	--	--	--	92	Surf.	Anchovy	12	0	0
							Bott.	Anchovy	8	0	0
60	5	Bott.	Bott.	11	38	30	Surf.	Anchovy	4	0	0
							Bott.	Anchovy	6	0	0
61	5	Bott.	Bott.	10	32	30	Surf.	Anchovy	9	0	0
							Bott.	Anchovy	9	0	0
62	5	J. 5′	Bott.	13	6.7	30	Surf.	Anchovy	11	0	0
								Grunion	1	0	0
								Kingfish	1	0	0
							Bott.	Anchovy	11	0	0
								Grunion	1	0	0
								Kingfish	2	0	0
63	5	J. 5′	Bott.	92	1.7	30	Surf.	Anchovy	10	0	0
								Pompano	1	0	0
								Kingfish	1	0	0
							Bott.	Anchovy	7	0	0
								Kingfish	1	0	0
64	5	J. 10′	Surf.	38	1.5	30	Surf.	Anchovy	7	0	0
								Pompano	1	0	0
								Jack mackerel	1	0	0
							Bott.	Anchovy	7	0	0
								Pompano	1	0	0
								Jack mackerel	1	0	0
65	5	J. 10′	Bott.	19	6.8	30	Surf.	Anchovy	4	0	0
								Pompano	4	0	0
								Jack mackerel	1	0	0
							Bott.	Anchovy	6	0	0
								Jack mackerel	3	0	0
								Queenfish	1	0	0
66	5	J. 10′	--	--	--	30	Surf.	Anchovy	4	0	0
								Queenfish	2	0	0
							Bott.	Anchovy	7	0	0
67	4	J. 20′	Bott.	25	7.8	92	Surf.	Anchovy	8	0	0
							Bott.	Anchovy	4	0	0

Some of the variation in the indicated kill is attributable to the fact that the test fish in some of the early trials, listed in Table 2 as Exps. 10, 13, 15, 16, and 20, were not dissected immediately and hence might have shown, on closer scrutiny, signs of injury (p. 347) that we construe as probably fatal. The peak intensity of shock recorded for these experiments is well above the apparent lethal threshold of 40 to 70 p.s.i. indicated by other experiments (as Exp. 17), and measured as indicated on p. 345.

Five-pound charges damaged fish at distances of about 65 feet (measured by hydrophone data in Exp. 19 and estimated from the jetted depth in Exp. 22). A pressure of 83 p.s.i., however, was recorded in Exp. 19 at the bottom cage where fish were apparently unharmed. It is probable that the fish were in the shadow zone (p. 362) of the focused compression wave.

The dampening effect of the bottom sediments on the shock wave was usually not great enough to eliminate the lethal effects of five-pound dynamite explosions, even though most of the trials were run where there is a very deep sedimentary overburden of clay-sand mixture, which is thought to be more effective than sand in decreasing the transmitted energy. The hard-rock surface here is presumably too deep to produce an effective reflection of the downward component.

With increase in depth of jetting there was, with some irregularities, a decrease in the observed kill. Large kills of free-swimming fish were recorded only for shots jetted less than 30 feet. At intermediate depths of jetting the kill was commonly greater in the surface than in the bottom cage. When the five-pound charge was jetted deeper than 35 feet (10 experiments, Nos. 13–22), there was usually little or no kill in either surface or bottom cage, or in the surrounding water. In two trials (No. 18, charge jetted to 45 feet, and No. 33, charge jetted to the greatest depth attained in any of the experiments, 65 feet), however, there was complete destruction of the fish in both cages. Clearly, the effects of dynamite explosions are difficult to interpret and unsafe to predict.

Two and One-half Pound Jetted Dynamite Charges

Caged fish were damaged in all three experiments (23–25) using 2½ pounds of 60 percent dynamite. Experiment 25 resulted in the killing of more free fish than any other during the entire test period. Forty-four jack mackerel, one Pacific mackerel, one midshipman, and one kelp pipefish were recovered. Approximately 300 additional jack mackerel were injured but did not surface completely. They were sufficiently incapacitated to make us believe that they probably would not have recovered before being preyed upon by predators, such as sea lions, several of which, in fact, soon entered the experimental area and probably fed on the injured fish. By diving, an attempt was made to estimate the total number of fish killed or damaged, but turbidity rendered the observations incomplete. Although it was estimated that the charge was jetted 35–40 feet into the sand bottom, the recorded peak pressure of 162 p.s.i. at the surface and the heavy kill suggest that the charge may have been inadvertently pulled to a shallower depth, or that the location of the charge very close to the underlying hard rock may have nearly doubled the intensity of the shock in the water. In the two other experiments no free-swimming fish were killed and the destruction of caged fish was about two-thirds and one-fifth, respectively.

One and One-quarter Pound Jetted Dynamite Charges

The lethal effects on fish of underwater explosions of jetted dynamite were by no means eliminated by a reduction of the charge to only 1¼ pounds. Free-swimming fish were killed by the two explosions at the jetted depth of 10 feet (Exps. 26–27), but none were destroyed in the nine trials (Exps. 28–36) in which the charge was jetted 15 to 30 feet. Of the nine experiments in which cages were used, there was a partial to complete kill of the caged fish in six trials. In Exp. 26, with the charge jetted to 10 feet, all 13 of the caged fish plus 5 free-swimming jacksmelt were killed. In Exp. 28, with the charge jetted to 15 feet, 45 out of 52 experimental fish were destroyed. In another trial (Exp. 29), with the same depth of jetting, all fish were killed; in yet another (Exp. 31), all survived. In Exp. 32, with the charge at 25 feet, there was a complete kill. In the three runs with the explosion at 30 feet the results were varied. In the whole series there was a heavy to complete kill when the peak p.s.i. was recorded as greater than 70, and little or no kill when the peak was below 60 pounds.

Four-pound Jetted Hercomite Charges

When it became apparent that even very small jetted charges of dynamite often kill fish, two trials were run with Hercomite powder (Table 3), in water 30 feet deep. Four-pound charges were jetted 20 and 30 feet, respectively. Peak pressures of 193 and 138 p.s.i. were recorded at the bottom cages, respectively 17 and 29 feet from the blast (measured instrumentally). These determinations indicate that the cages were directly over the blasts. All 36 fish in the surface as well as the bottom cages were killed in the two experiments. In two controls, the 19 fish used were unharmed. Though only the two experiments were run it seems probable that Hercomite resembles dynamite in its lethal effects on fishes.

Black Powder Charges

Strikingly different results were attained as soon as black powder (FFG and FFFG) was tried and rather consistent evidence accumulated

TABLE 5

Fish Killed During Oil Exploration Under Permit From California Department of Fish and Game September 4, 1951, to March 21, 1952

Pt. Conception to San Mateo Point

Number of fish killed per shot	Number of open shots	Number of jetted shots	Total shots
0	2,332	508	2,840
1	1	2	3
9	1	0	1
20	1	0	1
200	0	2	2
Total number of shots	2,335	512	2,847
Total fish killed	30	402	432
Average kill per shot	0.013	0.79	0.15

A maximum of 45 pounds of Hercules FFFG black powder was used on all work during the month of September, 1951; revision of permit effective October 1, 1951, allowed a maximum of 90 pounds of powder on both open and jetted shots. In general the practice has been to use 40 pounds of powder on jetted shots and the maximum of 90 pounds on open shots.

as the experiments were continued (Table 4). Very few fish were killed either inside or outside the cages, even when the weight of the charges was increased to 45 pounds and some of the charges were fired on the bottom and others were exploded just below the surface—in positions where dynamite is often very destructive. In the subsequently resumed seismographic surveys, according to reports by the state observers, extremely few fish have been killed, even by charges up to 90 pounds (Table 5).

In 17 experiments (Nos. 45, 47–49, 53–59, 62–67), in which from 4 to 40 pounds of black powder were exploded after having been jetted into the bottom sediments 5 to 20 feet, not a single fish death, on the basis of stringent criteria (p. 345), was recorded either inside or outside the cages.

In the two trials (60 and 61) in which five pounds of black powder was exploded on the bottom none of the fish was killed in cages held only five feet away, or in the overlying surface cages, or in the surrounding water. In two similar experiments (51 and 52), in which the cage was held only 10 feet away from a 10-pound black powder explosion on the bottom, none of the fish were killed in one trial, but half in the two cages were destroyed in the other. No free-swimming fish were killed in these experiments.

Ten-pound and twenty-pound charges of black powder when exploded just below the surface (Exps. 50 and 46) killed no fish anywhere. Subsurface explosions of 40 and 45 pounds (Exps. 41–44) varied in effect, depending apparently on either the type of container or the number of detonators employed. In two trials most of the fish in the surface cages were destroyed by 40-pound charges of black powder formed by binding together two sheet-metal containers five inches in diameter and 25 inches long, discharged by two detonators. Charges of similar weight in a shark-liver can with a single detonator caused no kill to caged fish only 20 feet from the explosion. That fish at somewhat greater distances are probably not killed by even such large charges of black powder is indicated by the fact that only one free-swimming fish, a mackerel, was destroyed in these four rigid tests. This was the only fish that was killed outside a cage in any of the 28 black powder experiments.

The resistance of fish to black powder explosions was dramatically exhibited in Exp. 54, in which 10 pounds of black powder exploded so close that the cage was badly damaged and partly covered with debris and the door was blown in (Figure 11). Though covered with mud, the two fish that failed to escape showed no signs of damage.

Effects of a jetted black powder shot are evident very soon—in about four or five seconds when the shot is in water about 30 feet deep. The large volume of suddenly generated gas carries mud and fine sand to the surface, forming a mushroom-shaped boil (Figure 12) that rapidly spreads over the surface. The resulting slick (Figure 13) usually has a diameter of 50 to 100 feet, depending on the size and depth of the charge. The amount of sand and mud that is brought to the surface seems to be relatively limited, for it forms only a superficial layer of murky water, below which clearer water can be observed. Jetted dynamite produces much less

FIGURE 11. Bottom cage damaged by 10-lb. black powder explosion No. 54. Remaining fish showed no damage. *Photograph by William W. Rand, April, 1951.*

FIGURE 12. Gas boil produced by a black powder explosion. *Photograph by William W. Rand, April, 1951.*

FIGURE 13. Slick following a black powder explosion boil. *Photograph by William W. Rand, April, 1951.*

11

12

13

gas and often no boil. The arrival of the shock wave from a dynamite explosion can be noted at a calm surface by the region of cavitation, which momentarily forms a small hump or dome.

In respect to both sound and shock the effects of black powder shots are relatively slight, as compared with explosions of dynamite or Hercomite. Frequently the jetted shots are barely audible and in the launch are often missed entirely. Black powder shots near the surface produce spouts 50 to 150 feet high, according to the size of the charge, but generate much less noise than do similar dynamite or Hercomite explosions.

The black powder explosions did not seem to have any conspicuous influence on the availability of game fish to sportsmen, as such fish were taken in the immediate vicinity soon after the shots were fired. They were apparently neither driven away nor deterred from feeding.

Explanation of Results

To explain the varied effects on fish life of underwater explosions it is desirable to examine and analyze individual components of the explosion complex, although, in general, the pattern of waves and other associated physical phenomena are quite complicated and, so far as we can learn, their interaction and the resultant forces are not completely understood. The most significant parameters are thought to be the amplitude (peak pressure), the type of compression wave, and rarefaction.

Underwater explosions produce two types of positive pressure waves, the initial compression or shock wave and the following bubble-pulse wave (Cole, 1948). The primary disturbance to the water during an explosion is caused by the arrival of the compression wave from the reacting explosive. Once initiated, the disturbance is propagated through the water as a pulse of compression with a leading front, which is steep (a shock front) or gentle, depending on the explosive used (Figures 8–9). The top of the pressure curve represents the peak pressure. In a uniform medium the peak pressure undergoes an exponential decay that is a function of the type of charge, its weight, and the distance from the charge. The peak pressure at a given distance is greater for larger weights, but increases only in proportion to the one-third power of the charge. The peak pressure from a given charge decreases with increasing distances. The rate of decay of energy varies with conditions. In open water the peak pressure from dynamite explosions is usually indicated as varying inversely as the 1.15 power of distance (not the 3.0 power assumed by Fitch and Young, 1948, p. 55). When the explosive is jetted into the bottom, the rate of energy decay is much greater. Data obtained during the experiments indicate that the approximate pressure near the bottom from jetted five-pound dynamite charges varies inversely as the 2.6 power of the distance (p. 345; Figure 10).

In either dynamite or black powder explosions the bubble pulse, shown at the right side in Figures 8 and 9, is relatively of long duration and low maximum pressure, without an abrupt front. In dynamite discharges, the bubble pulse has a maximum pressure far below that of the shock pulse. No indications were obtained that the bubble pulse from any of the explosions observed was of major significance in the destruction of fish.

The differential effects of dynamite and black powder explosions are attributable directly or indirectly to the abrupt shock wave produced by dynamite blasts. Dynamite detonates with a large and rapid evolution of energy, attaining its maximum intensity almost instantaneously. Once started, the disturbance is propagated through the water as a pulse of compression with a very steep shock front (Figure 8). Hercomite, to judge from its effects on fish in two experiments, resembles dynamite in its action, Black powder, in contrast, burns more slowly and does not produce a shock wave with an abrupt front (Figure 9). Nor, with comparable charges, is the peak intensity nearly so high. The lethal threshold peak pressures from dynamite explosions varied in our tests from 40 to 70 p.s.i. (as measured by the research engineers of the United Geophysical Company), whereas peak pressures from black powder explosions as high as 124 to 160 p.s.i. (similarly measured) did not kill fishes in the experimental cages (Tables 2, 4). One obvious reason why fish are resistant to black powder explosions, even of high intensity, is their relative immunity to less than almost instantaneous pressure changes. In other experiments fish subjected by us rather slowly to hydrostatic pressures as great as 1,000 p.s.i. showed no apparent physical damage, even after a relatively sudden release of the pressure. Positive pressure in the range of 15 to 500 p.s.i. (one to 33 atmospheres), even though maintained for a 12-hour period, produced, so far as could be observed, little immediate effect and no lasting discomfort or pathology. Regnard (1884) found that freshwater fish whose air-bladder had previously been emptied of air showed no effect when a pressure of 100 atmospheres of pressure was applied to them.

The reason why a large decrease in the weight of a dynamite charge results in unexpectedly little reduction in the kill is that the peak pressure does not bear a linear relation to the weight of the charge, but, rather, varies as the one-third power of charge size. A five-pound charge, for example, yields about one-third the peak pressure that a 125-pound charge does. The usefulness of a charge for seismographic work does not decrease in direct proportion to its reduced weight, but, similarly, the fish-killing powers do not decrease in that ratio.

It seems probable that the peak pressure from the black power explosions does not increase at as high a rate as does the pressure from dynamite blasts. E. Pat Shultz reports (in letter) that "With black powder increasing the charge size probably does not increase the peak pressure very much, but rather merely increases the duration of the pressure pulse. This is because the propagation rate of the burning is less than that of sound, and hence the full effect does not arrive at a distant point all at one time, as in a shock wave."

It was noted early in the experiments with dynamite that while fish in the surface cage were physically damaged by the blast, those in the bottom cage, nearest the explosion, often suffered no harm or less damage (Exps. 2, 3, 12, 14, 17, 19, 23, 25, 35). It was noted further that the free fish that were killed were mostly surface rather than bottom inhabitants. These observations can be explained in part only on the assumption that many bottom dwellers do not possess air-bladders and are therefore more resistant to explosions. Such bottom fishes as the kingfish, and others with large air-bladders, were found to be in the immediate area during some of the tests, but few were killed.

The greater mortality at the surface is probably caused by the intensity there of the rarefaction wave. It is assumed that, when reflected from the surface of a less dense medium, as from the water-air interface, a compression wave, if of sufficient amplitude, assumes the opposite sign through change of phase and is thus transformed, with some loss of energy, into a negative-pressure pulse, called a rarefaction wave (Cole, 1948). The suddenly applied negative pressure (considering atmospheric pressure as the base of reference) is probably particularly deleterious, even though, as Cole (1948) indicates, negative pressures as great as one atmosphere are not likely to be realized in natural waters, because of the dissipation of energy through cavitation.

In a system involving much less rapid changes, a negative pressure of 25 inches of mercury applied for a period of 15 seconds has been held to kill a number of freshwater species having air-bladders (Hogan, 1940). Preliminary experiments by us indicate that marine fishes with an air-bladder are quickly killed by negative pressures of between 20 and 30 inches of mercury, whereas those without an air-bladder survive such treatment.

That suddenly applied negative pressures kill fish appears to be indicated by the outward explosion of the air-bladders. In a report published by the Chesapeake Biological Laboratory it is stated that "post mortem observation showed that the edges of holes in the swim bladder were turned outward and that blood from broken vessels in the wall of the bladder had been blown into the abdominal cavity" (Anonymous, 1948). Similar observations were independently made during the experiments just concluded. Dynamite-destroyed kingfish had the visceral cavity filled with gas, which had obviously been released, under some pressure, from the ruptured air-bladder, thereby rendering the fish buoyant.

Negative pressure may cause injury or death in part through the formation of bubbles in the body fluids. We assume, in particular, that negative pressure may liberate dissolved gases suddenly enough and in sufficient quantity to rupture the walls of unprotected blood vessels.

The deadliness of the rarefaction wave is doubtless greatest near the surface. The negative-pressure wave is propagated downward through the water, but becomes sharply attenuated with distance and tends to be cancelled by the increase in hydrostatic pressure and, at certain times and locations, by the simultaneous arrival of compression waves reflected from the bottom.

The difference in deadliness to fishes of dynamite and black powder explosions is presumably due in part to much higher negative pressures induced by dynamite. Cole (1948 : 261) wrote that "in nearly all cases a negative absolute pressure is predicted for explosive waves of short duration." The wave from black powder blasts is of relatively long duration and low amplitude (Figures 8–9).

Large variations in fatalities in different cages may have been caused by the focusing of the path of the blast energy. The energy that is transmitted upward through the jet hole spreads out through the broad conical crater formed during the jetting (the craters were observed by diving). It is assumed that much of the energy emerging from the crater and from the surrounding bottom deposits is propagated through the water in a cone of similar form, leaving a shadow zone close to the bottom around the crater. The nine-cage unit was adopted in part to determine whether differential damage might be detected as a consequence of the directed energy. In Exp. 3, for example, there appears to have been such a focusing of the energy, for the kill was differential, with no deaths in the bottom cage nearest the crater but complete mortality in the directly overlying cages (compare data in Table 2 with the cage diagram, Figure 7). The compression pulse, measured at the surface, was 148 p.s.i., well beyond the lethal threshold recorded in the experiments (40–70 p.s.i.). That the margin of the cone of high pressure may be sharp is suggested by certain experiments, for example Exp. 19, in which fish were unharmed in the bottom cage although a gauge attached to the top of this cage registered a peak pressure of 83 p.s.i., also within the usual fatal dose.

Great variation was observed in the damage to fish caused by the underwater explosions. The variable factors appear to include, among others, the type and amplitude of the pressure pulse, the kind of bottom, and the structure and size of the fish. It is obvious that no simple explanation could be offered for all of the varied results, even though knowledge of the physical phenomena associated with fish and with explosives were much more complete than it is. The knowledge at hand, however, allows us to reach some plausible inferences.

As the pathological conditions of hemorrhaging, burst air-bladders, and general disruption of the viscera are shown by dissection and as the sequence of events of an underwater explosion are rapid compression soon followed by rarefaction, it appears reasonable to suspect that compression suddenly applied and rarefaction are the factors that lethally damage fish, particularly those near the surface.

CONCLUSIONS AND SUMMARY

This investigation arose from a conflict between different interests involved in the exploitation of the marine resources of California. Seismographic exploration for submarine oil had been suspended, through the revocation of licenses, because the explosions had destroyed large numbers of fish. The purpose of the study was to determine if the explosives might not be handled in such a way, as through a reduction in the size of charge or through altered methods, that most of the danger of killing fish would be eliminated.

Large charges of such violent explosives as dynamite—say from 50 to 200 pounds—were known to be very destructive to fish life. Considerable areas can be more or less depopulated by repeated blasts, as indicated by operations observed in a submarine canyon. Repopulation, however, took place within a few months.

Charges even as small as ten, five, two and one-half, or one and one-quarter pounds often killed fish, even when the explosive had been buried many feet in the bottom sediments. The amount of loss varied and was difficult to assess completely. Hercomite appeared to resemble dynamite in its effect on fishes.

The lethal effects of small charges of dynamite is in agreement with expectation, since the peak pressure varies as the one-third power of the weight of the charge. For example, a one-pound charge produces one-half the pressure that an eight-pound charge does. The effect of even large explosions becomes dissipated with distance, quite rapidly when the charge is jetted. For five-pound jetted dynamite charges used in these trials the peak pressure near the bottom varied as the 2.6 power of the distance.

The effect of underwater explosions of such substances as dynamite if often intensified at the surface, where the positive compression wave is reflected as a rarefaction wave. Fishes are very susceptible to negative pressures (that is, to pressures less than the atmospheric pressure). Black powder is much less effective than dynamite in producing such negative pressures.

Black powder explosions proved to be relatively inoccuous in a series of experiments, even with charges as high as 20 to 45 pounds, whether the charge was buried in the sediments, resting on the bottom, or suspended near the surface. These results were rather unexpected, though consistent with other observations. The resistance of fish to even larger black powder explosions is obviously due to the relatively slow burning quality of this powder. Oscillograms showed that the energy from black powder explosions is not propagated on the very abrupt front that emanates from a dynamite blast. Resistance to very large and relatively rapid changes in positive pressure is a known attribute of fishes, but they cannot tolerate the almost instantaneous changes induced by high explosives. The rigidly construed lethal-threshold peak pressures from dynamite explosions, as measured by the research engineers, varied from 40 to 70 p.s.i. in our tests,[2] whereas peak pressures from black powder explosions as high as 124 to 160 p.s.i. did not kill fishes in the experimental cages. Indications were obtained that black powder discharges do not even drive fish away or prevent them from feeding.

The experiments strongly indicated that it would be safe to utilize even large charges (to at least 45 pounds) of black powder, as a source of energy for submarine seismographic surveys. Unknown and untested factors, including the size of the fish and of its air-bladder, led us to make some reservations in judgment—reservations that could best be tested during actual operations, by observing the effects of such explosions on free-swimming fishes of varied sorts and sizes. Such checking has been maintained and the reports of recent surveys support the view that the use of black powder in charges as large as 90 pounds will not cause excessive loss of fish.

It would therefore appear that the State is not confronted with a problem of oil *versus* fish. The evidence leads to the conclusion that exploration for oil can be continued without the undue destruction of fish life. A major conflict of interests in the exploitation of our marine resources seems to have been resolved.

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[2] On the basis of less rigorous criteria of lethal effects, the reports of the Chesapeake Bay experiments (Anonymous, 1947, 1948) indicate a much higher lethal threshold for TNT explosions which, we understand, closely resemble dynamite explosions. On the theory that most fish severely injured by an explosion will in nature soon succumb through weakness, disease, or predation, we regard the more rigorous criteria as justified. Certainly it would not be safe to assume that internally injured fish will survive.

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FISH SPECIES MENTIONED

Only the vernacular names are used in the text. The species used in the 1951 experiments are marked by an asterisk (*), by a dagger (†), or by both, as explained on page 341. Some of these species and all those unmarked below, except the señorita, were killed in Scripps Submarine Canyon in 1950, as detailed in Table 1.

*Pacific sardine, *Sardinops caerulea* (Girard)
*Ocean northern anchovy, *Engraulis mordax mordax* Girard
Panama bristlemouth, *Vinciguerria lucetia* (Garman)
†Pacific saury, *Cololabis saira* (Brevoort)
Kelp bass, *Paralabrax clathratus* (Girard)
Sand bass, *Paralabrax nebulifer* (Girard)
*†Grunion, *Leuresthes tenuis* (Ayres)
†Jacksmelt, *Atherinopsis californiensis* Girard
Kelp topsmelt, *Atherinops affinis cedroscensis* Hubbs
*†Jack mackerel, *Trachurus symmetricus* (Ayres)
*California pompano, *Palometa simillima* (Ayres)
†Pacific mackerel, *Pneumatophorus japonicus diego* (Ayres)
Sargo, *Anisotremus davidsoni* (Steindachner)
*†Kingfish (tomcod croaker), *Genyonemus lineatus* (Ayres)
*†Queenfish, *Seriphus politus* Ayres
Ocean whitefish, *Caulolatilus princeps anomalus* (Cooper)
†Shiner seaperch, *Cymatogaster aggregata* (Gibbons)
Pink seaperch, *Zalembius rosaceus* (Jordan and Gilbert)
Buttermouth seaperch, *Embiotoca* sp.
†White seaperch, *Phanerodon furcatus* Girard
Sharpnose seaperch, *Phanerodon atripes* (Jordan and Gilbert)
Rubberlip seaperch, *Rhacochilus toxotes* Agassiz
Pile perch, *Damalichthys vacca* Girard
Blacksmith, *Chromis punctipinnis* (Cooper)
Garibaldi, *Hypsypops rubicunda* (Girard)
California sheepshead, *Pimelometopon pulchrum* (Ayres)
Opaleye, *Girella nigricans* (Ayres)
Señorita, *Oxyjulis californica* (Günther)
Bocaccio, *Sebastodes paucispinis* (Ayres)
Bass rockfish, *Sebastodes serranoides* Eigenmann and Eigenmann
Vermilion rockfish, *Sebastodes rosaceus* (Girard) (=*S. miniatus*)
Kelp rockfish, *Sebastodes atrovirens* (Jordan and Gilbert)
Widow rockfish, *Sebastodes ovalis* Ayres
Spotted rockfish, *Sebastodes hopkinsi* Cramer
Halfband rockfish, *Sebastodes semicinctus* Gilbert
Speckled rockfish, *Sebastodes umbrosus* (Jordan and Gilbert)
Rosy rockfish, *Sebastodes* sp. (=*S. rosaceus* of recent authors)
Greenspotted rockfish, *Sebastodes chlorostictus* (Jordan and Gilbert)
Pink rockfish, *Sebastodes eos* Eigenmann and Eigenmann
Starry rockfish, *Sebastodes constellatus* (Jordan and Gilbert)
Spanishflag, *Sebastodes rubrivinctus* (Jordan and Gilbert)
Striped rockfish, *Sebastodes elongatus* (Ayres)
Brown rockfish, *Sebastodes auriculatus* (Girard)
Whitebelly rockfish, *Sebastodes vexillaris* (Jordan and Gilbert)
Calico rockfish, *Sebastodes dalli* (Eigenmann and Beeson)
Treefish, *Sebastodes serriceps* (Jordan and Gilbert)
Rockfish (species?) ; very young, *Sebastodes* sp.
†Kelp pipefish, *Syngnathus californiensis* Storer
Crested goby, *Coryphopterus nicholsi* (Bean)
Zebra goby, *Lythrypnus zebra* (Gilbert)
Northern midshipman, *Porichthys notatus* Girard
†Slim midshipman, *Porichthys myriaster* Hubbs and Schultz
Spotted cusk-eel, *Otophidium taylori* (Girard)

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A Wave of Fish†

The California grunion is famous for swimming onto beaches at night at certain phases of the moon to lay its eggs. This remarkable set of photographs shows its near relative in the Gulf of Lower California performing its nuptial "dance" *in broad daylight*—a habit unknown until recently

By ANDREAS B. RECHNITZER
Scripps Institution of Oceanography
University of California, La Jolla, California

Photographs by GENE DANIELS, from BLACK STAR

DERS of NATURAL HISTORY
Magazine may recall having
the curious fish known as
union, which swarms onto
nia beaches in unbelievable
s at night to spawn.* These
ve never been known to
their appearance on the
coast beaches during the
.

interesting to note, there-
at on February 14, 1952, at
M., a near relative of the
nia grunion made a day-
awning run onto the beach
e tiny Mexican fishing vil-
San Felipe on the Gulf of
nia. Vacationists were as-
l to see hordes of the tiny
ggling on the sandy beach.
persons who were present
their sun bathing or surf
to sweep vast numbers of
thing fish into pots, pans,
any other container that was
Mr. Gene Daniels refrained
king up the grunion in or-
take these pictures of the
lar event.

her occasions, as well, the
nion, as distinct from the
a grunion, has been re-
as spawning during day-
rs in the recent past. Mr. David G. Jessop, of San Diego, found grunion spawning along the beach just in front of San Felipe village on February 19, 1951, at 4 P. M. The tide was high and ebbing at the time the grunion were on the beach. And the late Mr. Fred H. Wylie, a keen-eyed observer, also witnessed daylight grunion runs but on the opposite side of the Gulf at Cholla Bay, on April 23, 24, and 25, 1951. Each spawning was in the late afternoon just after the peak of the tide. As the greater part of the Gulf of California is, at best, sparsely populated, it is not strange that reports of the day-spawning Gulf grunion have been few.

In daylight the fish are an easy prey for gulls. But when the high spring tides occur during daytime, the Gulf grunion appear to do their spawning with total disregard for the daylight, despite the dangers. The supply of grunion is often so copious that gulls have been observed to stand and mope because they could not find space for another grunion in their gorged stomachs!

With the exception of these occasional daylight spawning runs by the Gulf grunion, its life history probably resembles that of the California grunion closely, and the two species are superficially quite similar in appearance. However, the taxonomists classify them in separate genera. They are labeled the California grunion, *Leuresthes tenuis,* and the Gulf form, *Hubbsiella sardina,* both belonging to the silversides family Atherinidae.

Grunion are found nowhere in the world except on the Pacific

NOTHING LIKE a grunion
n to get one close to nature

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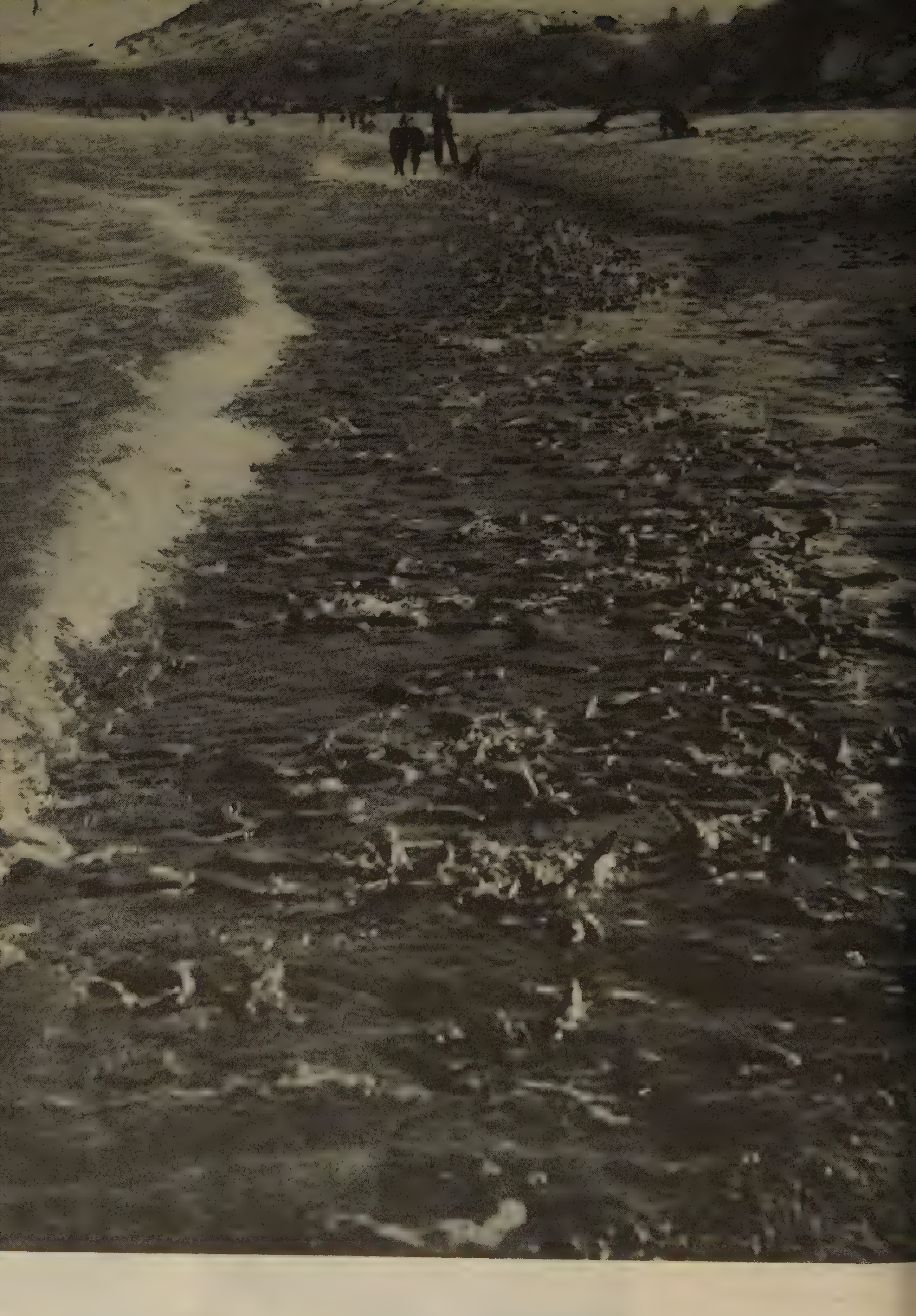
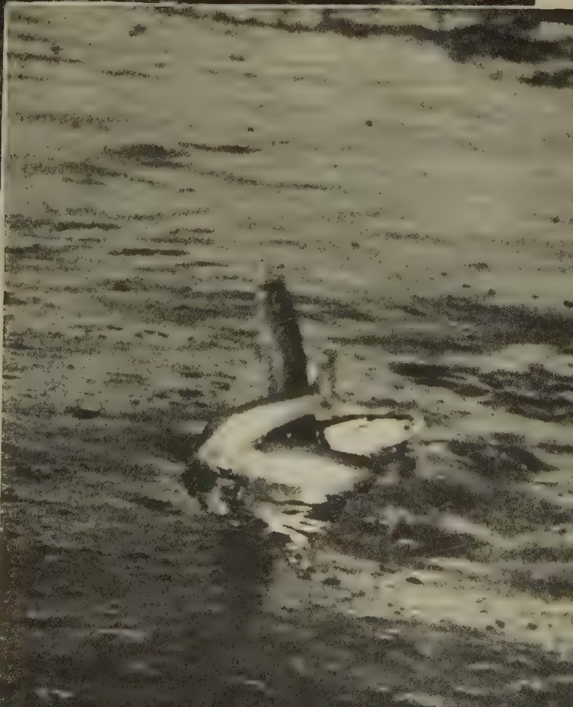
HISTORY for January, 1948



▲ A BEACHCOMBER'S DREAM. Bathed in warm sunlight, the grunion crowded onto the sandy shore at San Felipe. Many of the natives on the Gulf of California consider this a rare phenomenon

HALF BURIED in the sand, the females ap-
eared to stand on their tails



THIS UNUSUAL PHOTOGRAPH shows the actual mat-
g of the grunion. The upright female is burrowing
to the sand with rapid vibrations. She buries herself
ore than halfway, deposits her eggs, and returns to
e water in 30 seconds. Two or three male grunion
e curled around the female emitting their milt

coast from Monterey to southern Lower California, and in the Gulf of California. The grunion spends most of its life near the sandy beaches, and during the reproductive season it avails itself of the upper wave-swept beach area for spawning. Only during the spawning season, from February to September, do the fish come onto the beaches.

As the entire spawning act takes place out of water, the complete sequence of events can easily be observed during a daylight run like the one shown here. The fish swim in with the incoming waves. As a wave begins to recede, the fish deliberately swim shoreward in order to strand themselves as high up on the beach as possible. The female starts to dig in tail-first while there is still water on the beach. By rapid vibratory movements of her tail, she buries half her body or more into the semi-fluid, water-soaked sand. This "digging in" is accomplished very rapidly, often before the wave has completely run off the beach.

The male or males (the number attending one female varies) assume a curled position close to the female. While the female relieves herself of ripe eggs about two inches below the surface of the sand, the male curves his body around her and emits milt onto the sand close to her body. Although the milt is not applied directly upon the eggs, almost complete fertilization of the eggs is accomplished. Upon completion of spawning, which requires about 30 seconds, the grunion work their way back toward the water by vigorous wiggling and flipping, which usually frees them. Succeeding waves often assist the grunion to return to the water.

The wonders associated with this unique spawning do not cease with the laying of the eggs. Further relationships between the sand movements and the egg pods have been described by W. F. Thompson. He found that the eggs were normally deposited a couple of inches below the surface of the sand, but by the following day they were some four or more inches below the surface. This change in depth was found to be due to the building up of sand on the beach with the recession of the tide. Thus, after the eggs are spawned, they are buried still deeper by a deposit of wave-transported sand. The eggs are then better protected from surface predators, such as the godwit, a common sand-probing shore bird, as well as from dessication, abrasion, and rapid changes in temperature.

In their moist sand incubator, which is not visited by waves for two weeks, the embryos develop. Usually in seven days the eggs are ready to hatch. Even though the young grunion has developed sufficiently for hatching, it remains within the protective covering of the egg until the incoming tide washes the egg free. At this more opportune moment, the fish hatches and takes its first swim.

Apparently the egg has to be agitated in order to hatch. In the laboratory, eggs that were not agitated would go well beyond the normal two-week period, even though they were ready to hatch and were in water. After a little shaking, however, the tiny fish would scurry out of its egg case. The refusal of the egg to hatch until disturbed by a wave is of obvious advantage to the grunion.

The grunion's method of "going ashore" to spawn is unique among marine fishes and is bound to arouse astonishment in anyone who is fortunate enough to witness it.

▲ THE GRUNION were not so easy to catch as might be imagined. When approached, they would skitter back into the surf

▲ MOST OF THOSE who caught the fish regretted t bounty when the time came to scale and clean the

[AMERICAN JOURNAL OF SCIENCE, VOL. 251, MARCH 1953, PP. 231-236]

NOTES ON THE GEOLOGY OF GUADALUPE ISLAND, MEXICO

CLIFTON W. JOHNSON

ABSTRACT. Geological observations made in 1951 during a short visit to Guadalupe Island, Mexico, indicate the rock sequence to be almost entirely volcanic, with calcic andesite and basalt present. In the limited area studied at the south end of the island, the section is composed of hornblende andesite and cemented tuff. A lithified tuffaceous marl interbedded within the volcanic series contains a marine fauna probably representing the Upper Tertiary or Quaternary. Inner Island, lying off the southern tip of Guadalupe, presents a fine cross-section view of an eroded cinder cone.

INTRODUCTION

DURING the month of August, 1951, the writer and his colleagues, Commander C. N. G. Hendrix, U.S.N., Dr. Edwin L. Hamilton, Navy Electronics Laboratory, San Diego, California, and Mr. Robert Fisher, Scripps Institution of Oceanography, La Jolla, California, participated in a six-day bathymetric survey conducted from the auxiliary schooner *E. W. Scripps* in the waters surrounding Guadalupe Island, Mexico, longitude 118° W., latitude 29° N., about 200 miles southerly from San Diego, California, and 150 miles westerly from the peninsula of Baja California, Mexico (fig. 1). The longitudinal axis of the island lies in a north-south direction extending 20 miles, with the width varying from 3 to 7 miles. Two small islands known as Inner Island and Outer Island, each less than ½ mile in diameter, lie within a 2-mile radius of the southern end of Guadalupe Island.

The topographic aspect of Guadalupe Island is one of bold relief with sea cliffs rising abruptly along most of the coastline to elevations in the 2000- to 3000-foot range (plate 1). Available maps differ in the contour of coastline and topography. The maximum elevation is usually given as 4038 feet and occurs near the north end of the island. Safe deep water anchorages close inshore are limited to Northeast Anchorage and Melpomene Cove (fig. 2) at the south end of the island. Vegetation is sparse, the higher slopes dotted with a scant growth of what appears to be Guadalupe pine, oak and cypress as described by Hanna (1925). Intermittent rainfall records indicate an annual precipitation of 3 to 5 inches. Some additional moisture is derived from frequent dense cumulus clouds which shroud the highest elevations during most of the year.

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*Contribution from the Scripps Institution of Oceanography, New Series, No. 578.

Coincident with the bathymetric survey, landings were made at Melpomene Cove and Northeast Anchorage for the purpose of studying rock relationships. A small boat approach was made to the vertical walls of Inner Island where hand specimens were obtained. The purpose of this note is to describe and figure the unusually fine exposure of an igneous intrusion on the seaward or west side of Inner Island and to present a short discussion of the rock sequence in the Melpomene Cove area.

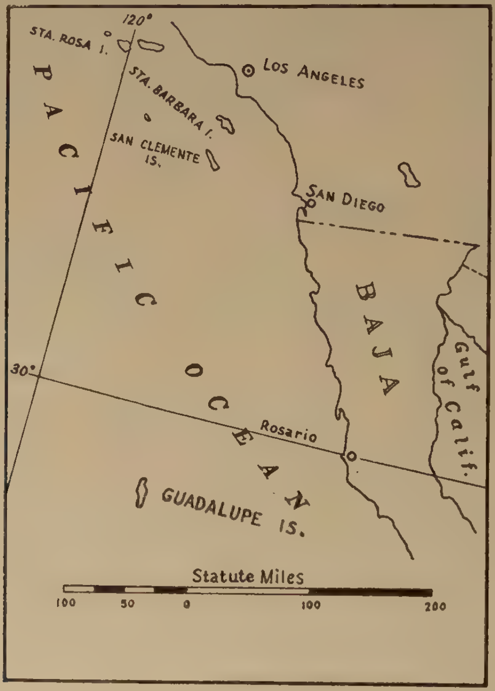
120°
STA. ROSA I.
LOS ANGELES
STA. BARBARA I.
SAN CLEMENTE IS.
SAN DIEGO
PACIFIC OCEAN
BAJA
Gulf of Calif.
30°
Rosario
GUADALUPE IS.
Statute Miles
100
50
0
100
200

Fig. 1. Index map.

ACKNOWLEDGMENTS

The writer is greatly indebted to Dr. Roger Revelle, Director, Scripps Institution of Oceanography, La Jolla, California, and

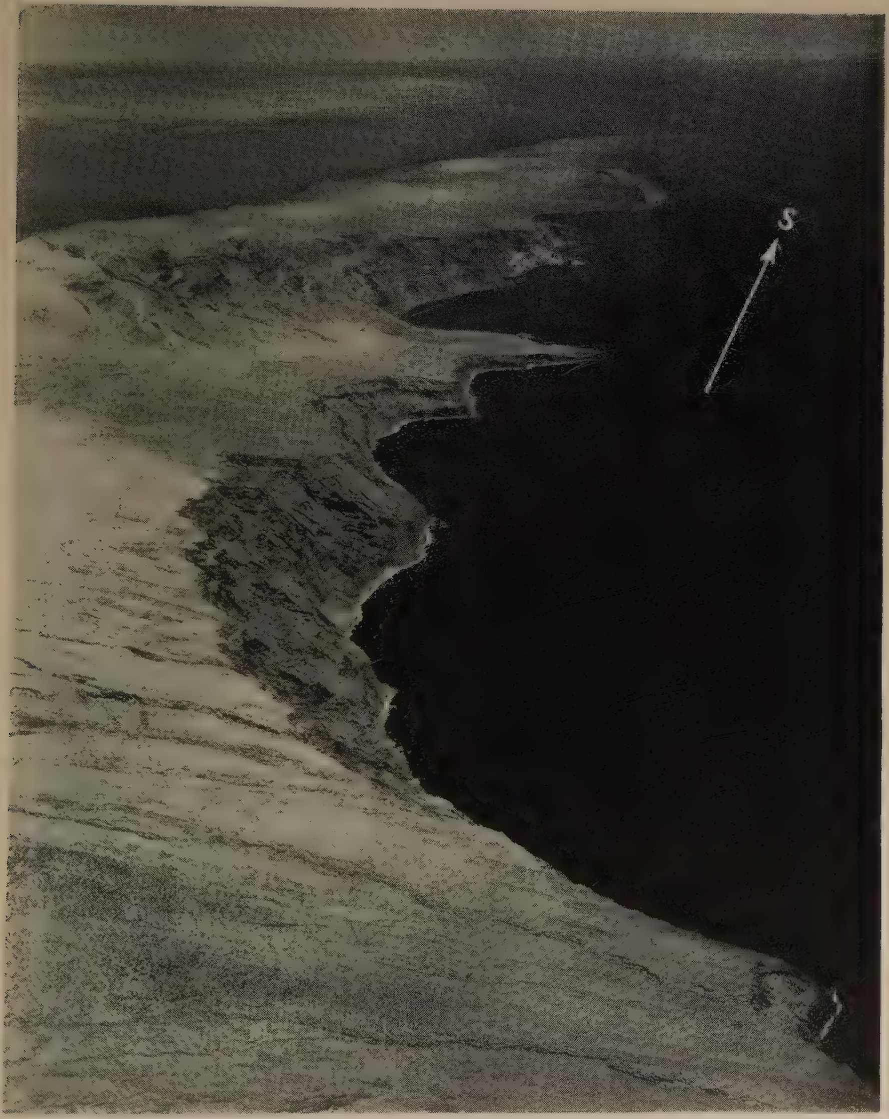

Plate 1. Southwest coastline.

Plate 2

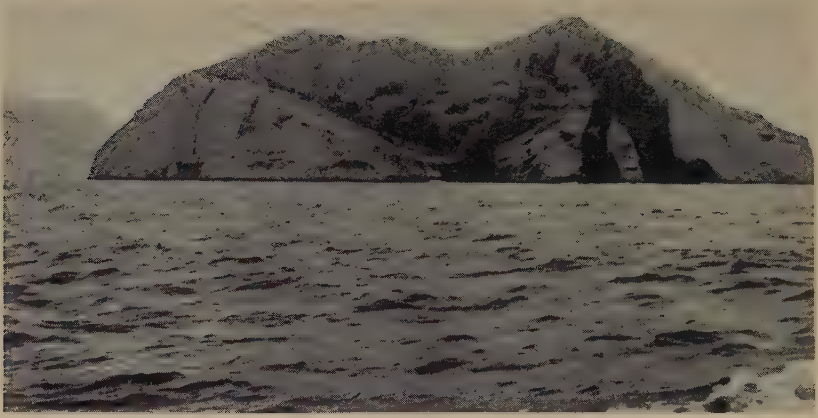

Fig. 1. Inner Island.

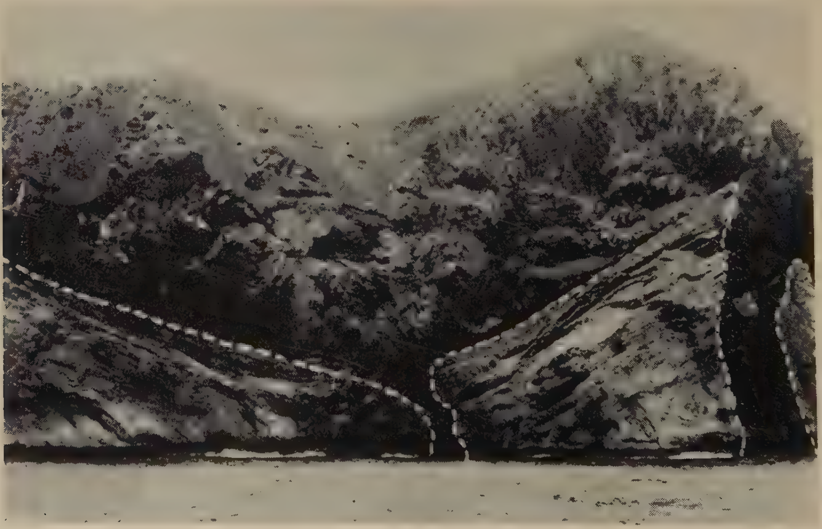

Fig. 2. Inner Island—close-up.

to Dr. Robert S. Dietz, U. S. Navy Electronics Laboratory, San Diego, California, for permission to become a member of the August 1951 expedition to Guadalupe Island and to use data compiled during the cruise. Especial thanks are due Commander C. N. G. Hendrix, U.S.N., Dr. Edwin L. Hamilton, and Mr. Robert Fisher, members of the expedition, for their enthusiastic assistance in many ways. Dr. Charles A. Anderson, U.S.G.S., Prescott, Arizona, kindly made available his field notes taken during a visit to the Island in 1940. The writer is indebted to Professor A. O. Woodford, Department of Geology, Pomona College, Claremont, California, for aid in thin section determinations and helpful criticism of the manuscript. Credit is due Dr. M. L. Natland, Chief Paleontologist, Richfield Oil Corporation, Long Beach, California, for fossil determinations referred to in this report. The aerial photograph showing the southwest coastline of Guadalupe Island was made available through the courtesy of the U. S. Coast and Geodetic Survey.

GEOLOGIC NOTES

During the course of the bathymetric survey numerous close approaches were made to the rugged coastline affording ample opportunity to observe the general distribution of rock types. The principal rock type studied proved to be calcic andesite, usually showing flow structure and occasionally a pahoehoe surface. Observed attitudes of flow structure are usually low, suggesting initial dip and absence of deformation. It is estimated that some 20 per cent of the exposed rocks may be classed as pyroclastic. Tuff and agglomerate varying in color from light pink to buff and gray occur sometimes interbedded with calcic andesite flows, but more frequently as mantle deposits on the most recent andesite surfaces. Here the well-bedded pyroclastics slope away from essentially undissected cinder cones perched along the backbone of the island. In the southern portion outbursts from closely spaced cones have resulted in the coalescence of pyroclastic deposits with resultant discordant bedding. There was no observed indication of deformation in the pyroclastic series.

The sea cliff along the northerly shoreline of Melpomene Cove reveals a volcanic series 200 feet thick with regional 5° southerly dip and a plateau surface. Massive calcic andesite predominates with an aggregate of about 50 feet of tuff present as

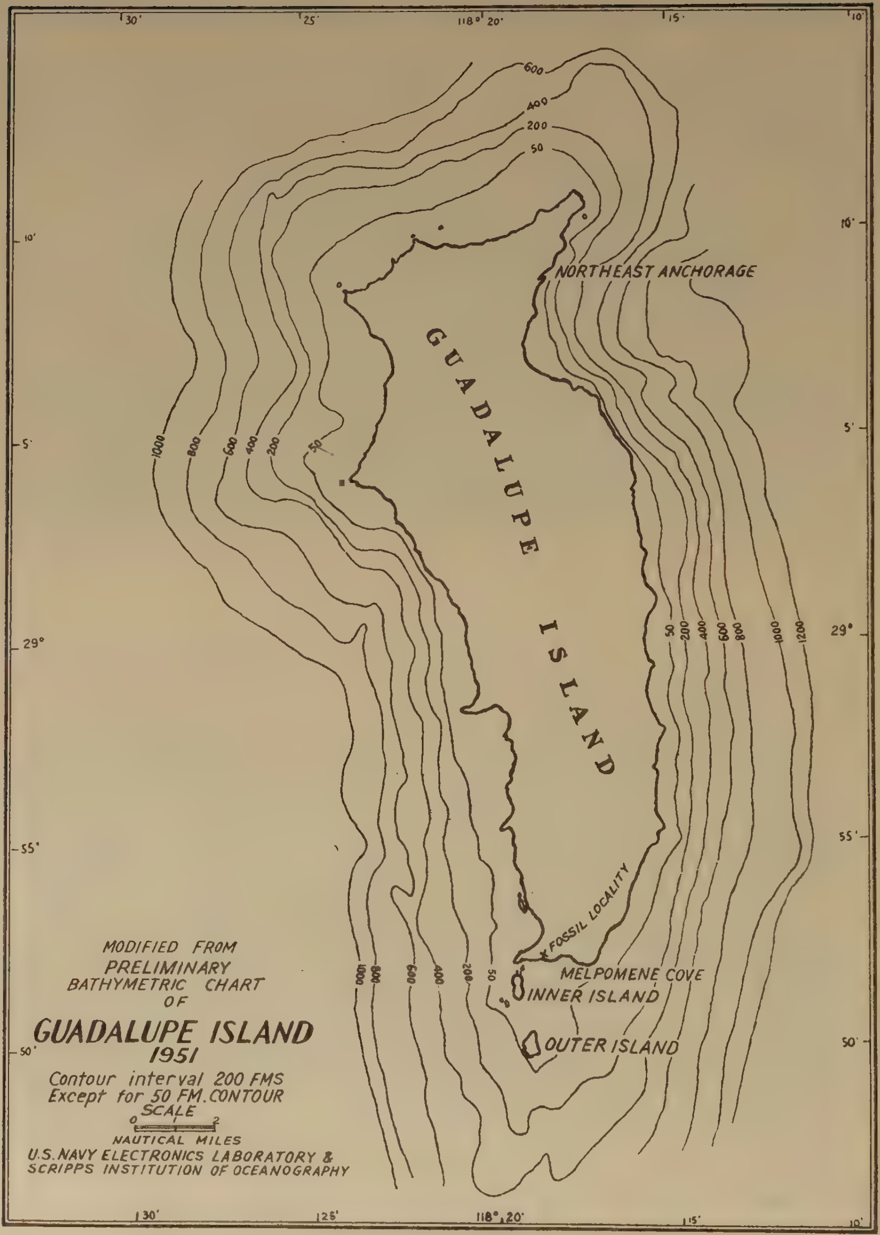
30'
25'
118° 20'
15'
10'
10'
5'
29°
55'
50'
600
400
200
50
1000
800
1200
GUADALUPE ISLAND
NORTHEAST ANCHORAGE
FOSSIL LOCALITY
MELPOMENE COVE
INNER ISLAND
OUTER ISLAND
MODIFIED FROM PRELIMINARY BATHYMETRIC CHART OF
GUADALUPE ISLAND
1951
Contour interval 200 FMS
Except for 50 FM. CONTOUR
SCALE
0 2
NAUTICAL MILES
U.S. NAVY ELECTRONICS LABORATORY & SCRIPPS INSTITUTION OF OCEANOGRAPHY

Fig. 2. Bathymetric map.

interbeds from 1 foot to 10 feet in thickness rather uniformly distributed throughout the section. In hand specimen the andesite appears unweathered, usually shows flow structure, and is often vesicular. Preliminary study of a thin section representative of the vesicular phase indicates a mineral assemblage of hornblende andesite with numerous phenocrysts of labradorite (An 50-55) and basaltic hornblende. The latter has broad, opaque reaction rims with radial structure apparently made up of hematitic material. Magnetite and augite are also present. Numerous vesicles are partially filled with low index colorless minerals, probably including chalcedony. The groundmass is composed mainly of minute lathlike calcic andesine grains. This rock is similar to the calcic andesite of the Glendora volcanics, Los Angeles County, California, as described by Shelton (1946). Some specimens of basalt (?) show common olivine phenocrysts in an aphanitic groundmass.

Samples of the pyroclastics are characteristically buff to tan lithic tuff, often containing lapilli of pumice and vesicular basalt. A thin section from the lithic tuff exposed near the present plateau surfaces shows the main constituent to be glass containing microlites, most of which are plagioclase altering to orange-yellow chlorophaeite. Euhedral grains of basaltic hornblende, olivine, and magnetite occur in that order. Occasional vesicles appear to be filled with chlorophaeite. On the surface of the plateau there is a most remarkable occurrence of residual sand originating from the volcanic landscape. Loose deposits of very fresh, euhedral grains of plagioclase, basaltic hornblende, and olivine up to ½ inch in length lie in depressions where they have been collected by the sweep of the strong prevailing westerly winds. A sample of tuff from Inner Island appears to be palagonitic with numerous minute vesicles.

It has been noted by Anderson, in a personal communication, and also by the writer that certain outcrops of the pyroclastics exhibit excellent stratification and cross-bedding suggestive of water deposition. Mr. Hamilton of our landing party found in these beds what are believed to be the first fossils from Guadalupe Island. A hand specimen of lithified tuffaceous marl from the Melpomene Cove seacliff, about 75 feet above sea level and interbedded within the pyroclastic series, yielded a marine fauna which has been identified by Dr. M. L. Natland. The fossil material was collected along a path skirting the seacliff about 500 feet easterly from the weather station maintained by the Mexican government. Dr. Natland comments: "The sample of lithified tuffaceous marl interbedded with volcanics on Guadalupe Island contains an unidentifiable, small (maximum diameter 1.00 mm.) unornamented, pearly-lustered gastropod. Many foraminiferal specimens similar to *Anomalina schmitti* were dislodged intact from the rock. In general they are thicker and have a larger umbo than the Southern California Recent and Tertiary specimens. A thin section of the material contained cross sections of *Discorbis cf. rosaceus, Miliolidae,* Echinoid spines, and fish scales. Until more material is collected from the area no positive age assignment is possible other than that it is probably Upper Tertiary or Quaternary. The fauna indicates a shallow water marine environment."

Similar andesite, basalt, and pyroclastic rocks widely exposed throughout the southern portion of the peninsula of Lower California have been designated Quaternary to Miocene by Beal (1948, pp. 74-77 and 84-85), Anderson (1950, pp. 11-14), and others.

Inner Island, located about ½ mile south of the southerly tip of Guadalupe Island, rises to an elevation of 600 feet, and is about 1500 feet in width at sea level. Viewed from the east, Inner Island appears to be entirely composed of low-dipping, tan-colored, lithic tuff with sporadic angular blocks of basic flow rock.

The western seacliff of Inner Island (plate 2, fig. 1)presents a "textbook illustration" of the phenomena associated with igneous activity along a volcanic conduit. Apparently the most recent epoch of volcanic activity included the rise of basic magma through a central conduit about 20 feet in diameter. The dikes (plate 2, fig. 2) visible on the right side of the central neck are probably contemporaneous. A baked tuff zone, brick-red in color and approaching 25 feet in width, is present along the margins of the dikes and central conduit.

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RICHFIELD OIL CORPORATION
LOS ANGELES, CALIFORNIA

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The distribution of some heteropod molluscs off the Pacific coast of North America.*

By

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Sir John Cass College, London.

[Received January 1, 1952.]

(With 7 figures in the text.)

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INTRODUCTION.

Although the heteropod molluscs are well known for their adaptations for a pelagic mode of life, virtually nothing is known of their ecology, and it is mainly the recent work of Tesch (1949) in clarifying the distinction between the different species which has made any ecological studies possible. In this paper an account is given of the distribution of the larger heteropod genera, *Carinaria*, *Pterotrachea* and *Firoloidea*, in the north-east Pacific over a period of one year from February 1949.

The area surveyed extended from Cape Disappointment, Oregon (about 47° N.), to Punta Santa Eugenia, Mexico (about 27° N.), a distance of over 1,500 miles and offshore for about 500 miles (fig. 1). Cruises were made at monthly intervals, each cruise lasting about two weeks, usually three ships being employed simultaneously to take samples at approximately 120 stations arranged in twelve lines (extending at right angles to the coast) of 10 stations each, evenly distributed over the area in fig. 1. The plankton net used was about 5 m. in length, supported by a ring 1 m. in diameter, and had mesh-apertures approximately 0·65 mm. across. Oblique hauls were taken from a depth of about 75 m., the volume strained at each haul varying from 500–1,000 cubic metres, measured by a current meter suspended in the opening of the net. As heteropods are essentially surface-living animals occurring mainly between the surface and 100 m. these samples probably give a rough indication of their horizontal distribution. There was no significant difference in the numbers taken at night from those taken during the day. The samples were fixed in dilute neutralized formalin and the state of preservation of the heteropods was good. The shells of the *Carinaria* were usually missing, but many specimens were obtained with perfect shells.

The material was sorted from the plankton samples obtained as part of the California Cooperative Sardine Research Programme, of the California Academy of Sciences, the Bureau of Marine Fisheries of the California Division of Fish and Game, the South Pacific Investigations of the U.S. Fish and Wildlife Service, and the Scripps Institution of Oceanography of the University of California.

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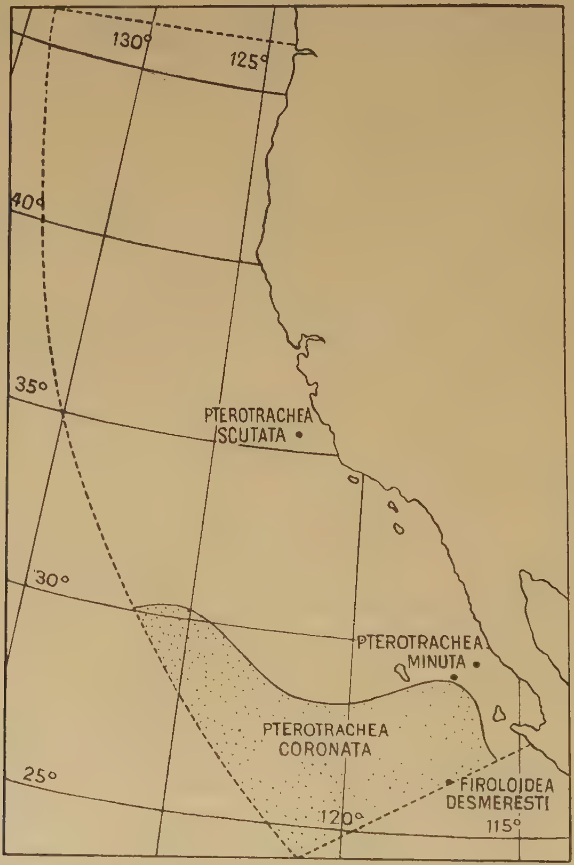
* Contribution from the Scripps Institution of Oceanography, New Series, Number 579.

I am greatly indebted to these Institutions for supplying physical and field data, and particularly to Professor Martin W. Johnson of the Scripps Institution of Oceanography, where this work was carried out, for every assistance in placing the samples at my disposal for analysis. I also wish to thank Dr. J. J. Tesch for kindly checking my identification of the *Carinaria*, representative specimens of which have been placed in the British Museum (Natural History).

Pterotracheidae.

All four species of *Pterotrachea* enumerated by Tesch occur in this area, although one, *P. hippocampus* is by far the most numerous. The others, together with *Firoloidea desmeresti* are rare, only one or two individuals having been collected. With the exception of the single *P. scutata* which was found, all the pterotracheids were taken in the most southerly part of the collecting area. It is therefore possible that although none of the pterotracheids were numerous within the area sampled, they may be more adundant below 27° N.

Figure 1.



Distribution of *Pterotrachea coronata, P. scutata, P. minuta*, and *Firoloidea desmeresti*. The broken line shows the limit of the sampling area.

Pterotrachea scutata Gegenbaur.

A single female between 100 and 110 mm. in length was taken on 6th March, 1949, at the point shown in fig. 1.

Pterotrachea minuta Bonnevie.

Two females were taken on different occasions: one on 7th May, 1949 was 10–20 mm. in length, the other taken on 2nd June, 1949 was 20–30 mm. long. They were collected from the places shown in fig. 1.

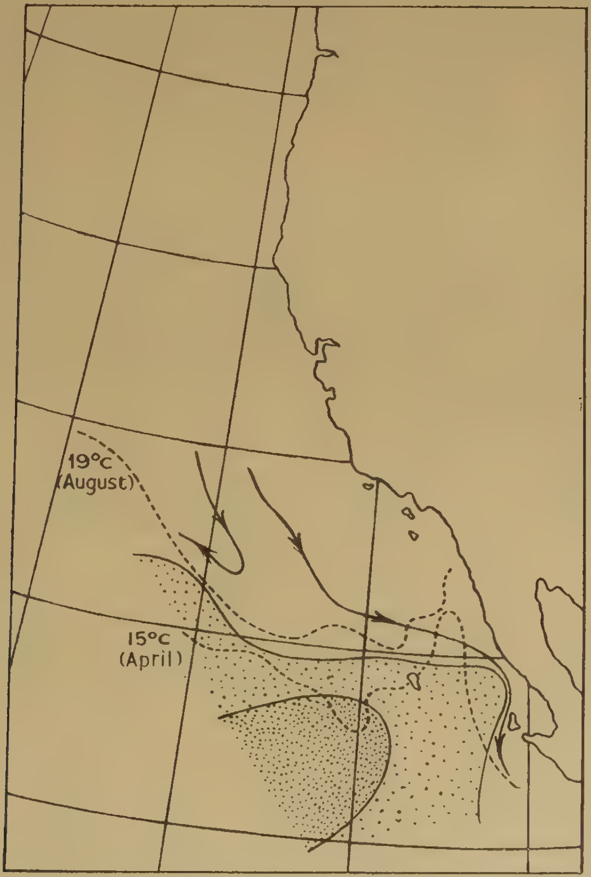
Pterotrachea coronata Forskål.

A total of eight individuals was collected, all females, ranging in length from 20–30 mm. to 90–100 mm., and having a mean length over the whole period of 59 mm. All were collected between February and September within the area shaded in fig. 1.

Pterotrachea hippocampus Philippi.

The only common pterotracheid in the area; a total of seventy-eight specimens was obtained, of which twenty-six were males. Specimens were found over a larger area during summer than in the early spring (fig. 2). All were taken between March and September, and none found between October and the following February. An estimate of the population density at different

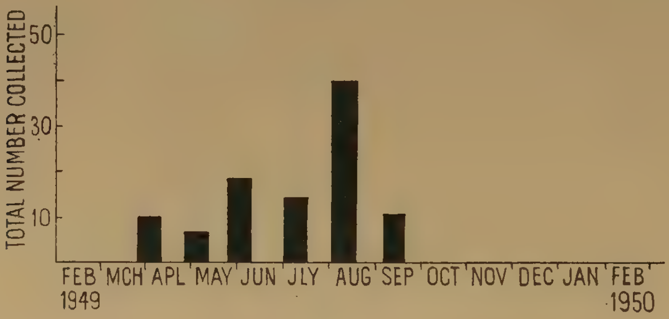
Figure 2.



Distribution of *Pterotrachea hippocampus*. The area heavily stippled shows the limits of distribution in spring; the area more lightly stippled, the distribution in late summer. In this, and in the following figures, the continuous lines with arrows show the general current pattern; broken lines, surface isotherms.

times of the year has been made by correcting the number present in any sample to the number expected to be present in 1,000 cubic metres (fig. 3).

Figure 3.



Total number of *Pterotrachea hippocampus* taken at different times of the year. (The number in each sample corrected to 1,000 cubic metres.)

Firoloidea desmeresti Lesueur.

A single male, 20–30 mm. in length, was collected on 7th June, 1949, at the point shown in fig. 1.

Carinariidae.

Carinaria lamarki Péron et Lesueur.

Only one species of *Carinaria* referable to *C. lamarki* has been found in the area. It agrees well with previous descriptions of the species, but differs in the remarkably high tail-crest which is shown even in specimens only 3 or 4 mm. in length. None of the specimens have the quadrate fin of *C. australis* Quoy et Gaimard (=*C. lamarki* Péron et Lesueur) described from the south Pacific. Other species of *Carinaria* recorded elsewhere from the north-east Pacific (*vide* Tesch) have not been collected.

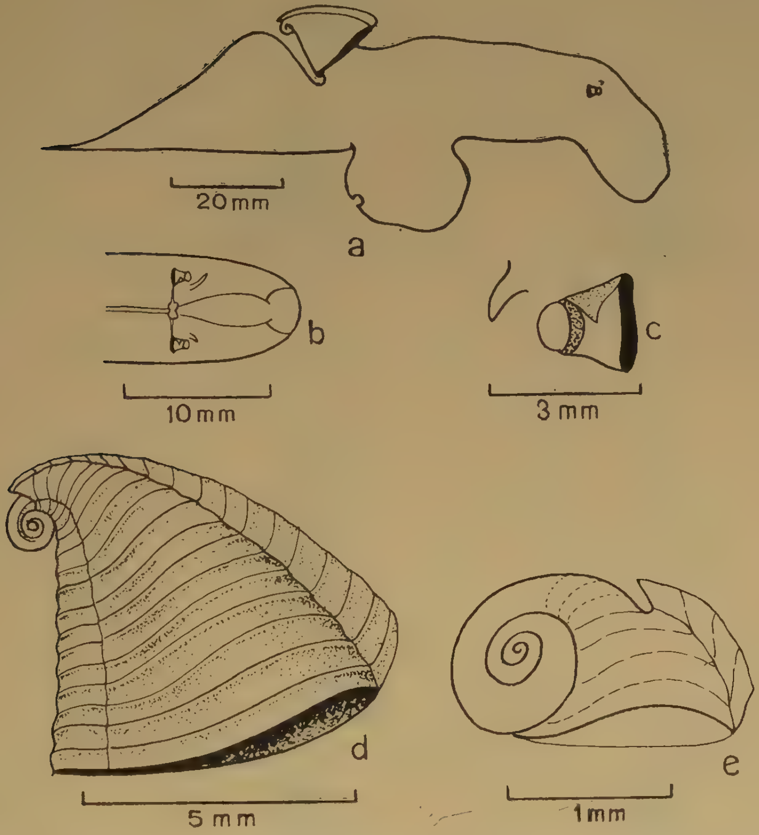
Description of specimens collected during the present investigations :

Specimens of each sex up to 130 mm. in length. Shell usually chalky, about as broad as high, with a keel less than one-fifth the breadth of the shell aperture (fig. 4 *d*, *e*). Eye conical, the diameter of the base equal to the distance from its centre to the front surface of the lens (fig. 4 *c*). Both tentacles present, but the right much smaller than the left (fig. 4 *b*). Ventral fin slightly broader than deep, and wider at the middle than at the base. Tail-crest prominent fig. 4 *a*). Tubercles usually not obvious in small specimens, but more prominent in older ones, being most noticeable along the ventro-lateral region of the trunk and above the base of the ventral fin. Specimens more than about 100 mm. in length with black pigment along the margins of the ventral fin and tail.

Over nine hundred specimens of this species were collected over the whole period, males and females being present in approximately equal numbers. An estimate of the population density on each cruise is shown in fig. 5, the numbers having been corrected in the same way as in fig. 3 ; the size-distribution of specimens collected during each cruise is shown as a series of histograms in fig. 6.

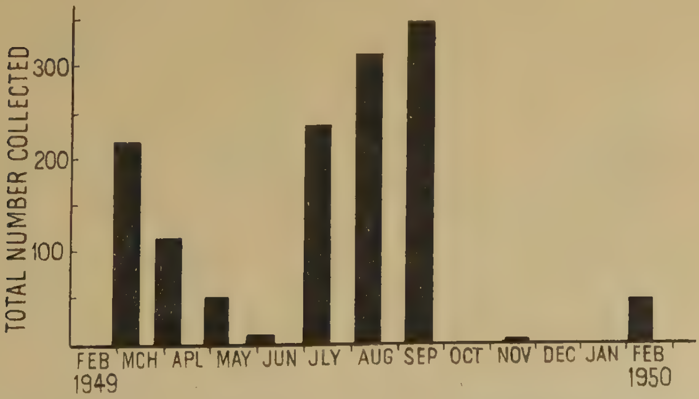
It will be seen from fig. 5 that the total number declined towards early summer, but increased steadily during late summer ; an almost complete disappearance followed by November. The reason for this disappearance is not known, but may be due merely to the change to winter conditions. The

Figure 4.



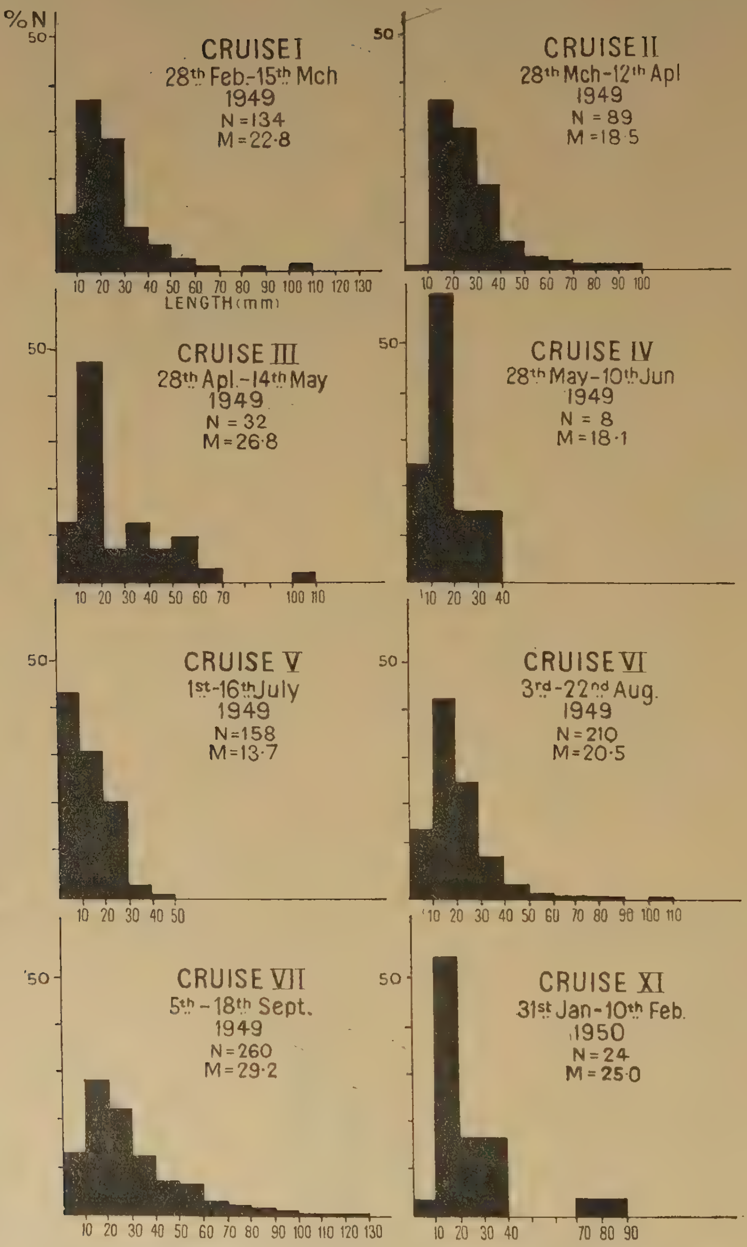
Carinaria lamarki. (*a*) An adult specimen from the right side, showing the elevated tail-crest; (*b*) the head of a specimen 45 mm. in length from above, showing the relative lengths of the left and right tentacles; (*c*) eye and left tentacle of an adult specimen; shells from (*d*) an adult, (*e*) a young specimen.

Figure 5.



Total number of *Carinaria lamarki* taken at different times of the year. (The number in each sample corrected to 1,000 cubic metres.)

Figure 6.



Size-distribution of *Carinaria lamarki* at different times of the year.

seasonal occurrence and disappearance of heteropods has been noted before (*vide* Tesch).

The main spawning period undoubtedly occurs during May, the percentage of larger specimens falling steadily with a corresponding decrease in the total numbers taken over the spring months. By July over 40 per cent of the total number collected were under 10 mm. in length. The mean length of all the individuals over the whole area gradually increased until in September the mean length was about 30 mm., and over 10 per cent of the total number collected were more than 70 mm. long. The only specimen taken in November was a female over 80 mm. in length, but in the following February over 90 per cent of those collected were under 40 mm. in length. It is possible, therefore, that a second spawning took place in late September, and if this were so, the disappearance in autumn may have been due partly to the spent individuals having died. More intensive collecting is clearly necessary to settle these problems.

The actual distribution of the *Carinaria* over the area is shown in fig. 7. Distribution maps have been constructed only for those cruises which collected a relatively large number of specimens. The distribution seems to bear some relation to the current pattern, in that the areas where the maximum numbers occur often reflect the current contours. Although a vast amount of physical data on temperature, salinity, oxygen, phosphate content and so on, has been collected, it is doubtful whether the data have much significance in relation to the present work. The only general conclusion which may be drawn is that the maximum numbers of *Carinaria lamarki* appear to occur in regions where upwelling takes place, but apart from this the distribution cannot be related directly to environmental factors. Consequently only a few surface isotherms have been inserted to indicate the conditions existing at the time of sampling. It is not surprising that the *Carinaria* are more numerous in the regions where upwelling occurs since the waters are generally richer in other organisms on which the heteropods feed. The absence of pterotracheids from these areas might be ascribed to their higher temperature requirements.

CONCLUSIONS.

With the exception of the single *Pterotrachea scutata* which was collected rather more than 35° N. when the surface temperature was 12° C., the species of *Pterotrachea*, together with a single specimen of *Firoloidea desmeresti*, have seldom been collected north of 30° N. and then only when the surface temperature was less than about 15° C. *Carinaria lamarki*, on the other hand, has been collected over the whole area surveyed as far north as 45° N. and in temperatures not less than 10° C. at the surface, but is most numerous between 35° N. and 40° N. and 115° W. and 130° W. Most previous authors have found that heteropods do not extend further than 40 from the equator, but *C. lamarki* seems to have an exceptionally broad range and previous writers have found it beyond 50° N. (*vide* Tesch). *Pterotrachea hippocampus* as the only species of *Pterotrachea* that was numerous, and *Carinaria lamarki* the only species of *Carinaria* collected. These *Carinaria* differed from previous descriptions of *C. lamarki* in the more elevated tail-crest. They may be referred to *C. lamarki* from the character of the shell, but it is possible that they represent a distinct subspecies. The elevated tail-crest was a uniform feature of all the specimens seen from this region; it does not appear to be so prominent in individuals from the Atlantic. That there is this slight anatomical difference is not surprising when one considers the apparent isolation of this population (fig. 7). Unlike *C. lamarki* in which the males and females are present in approximately equal numbers, females of all the *Pterotrachea* species are more numerous than the males. *Carinaria lamarki* may spawn throughout the year, but certainly mainly in later April or May, and possibly also in September.

The *Carinaria* were only rarely found in plankton dominated by copepods, euphausiids, or other crustaceans, and were characteristic of plankton consisting mainly of salps, coelenterates and chaetognaths.

Figure 7.

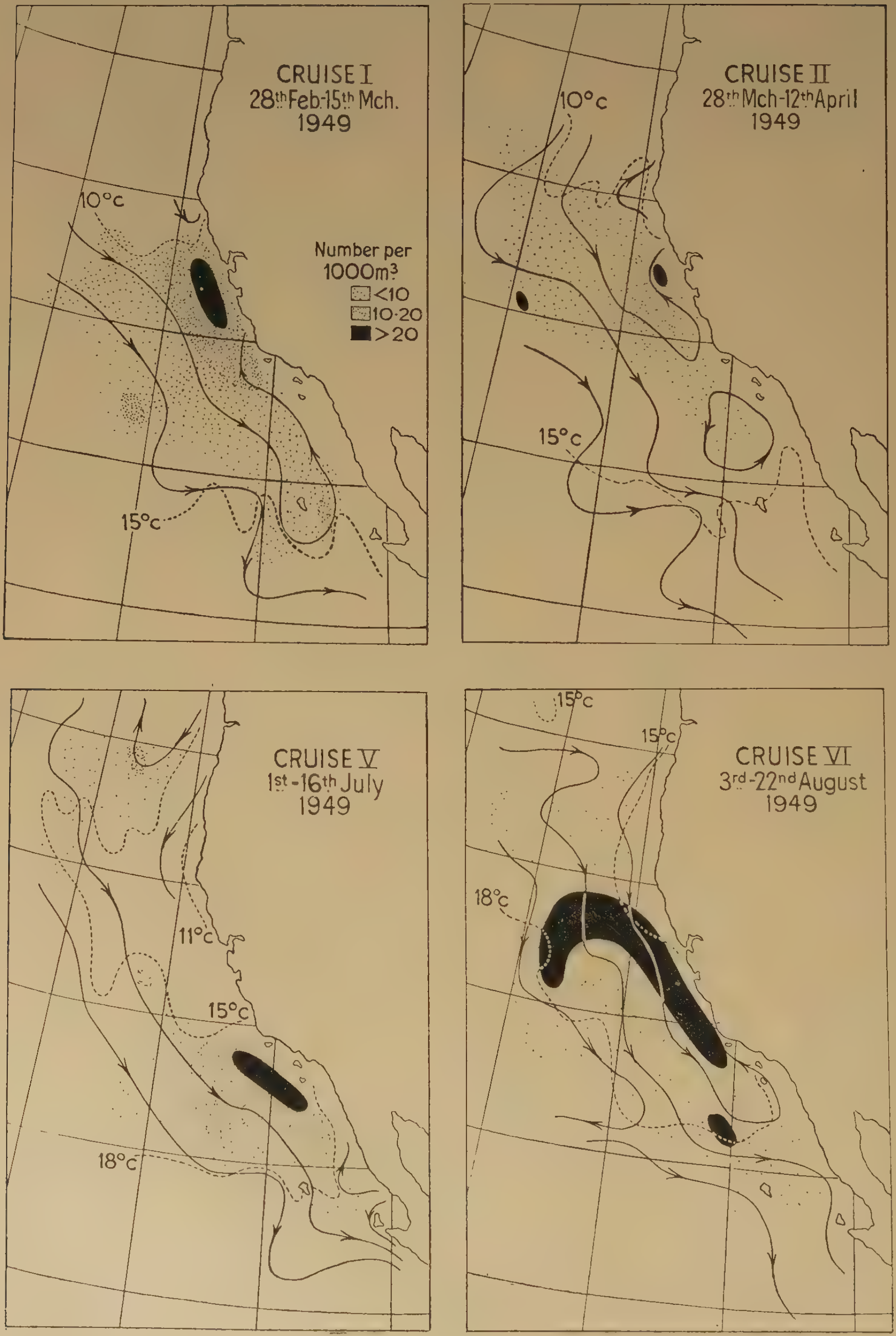
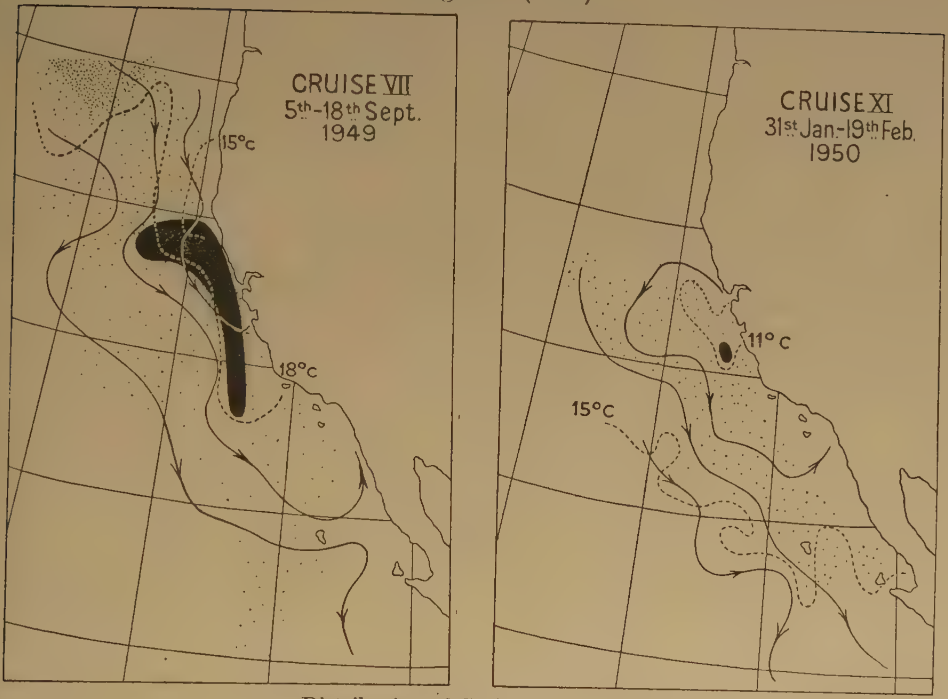

CRUISE I
28th Feb-15th Mch.
1949
10°c
15°c
Number per
1000m3
▨ <10
▨ 10-20
■ >20
CRUISE II
28th Mch-12th April
1949
10°c
15°c
CRUISE V
1st-16th July
1949
11°c
15°c
18°c
CRUISE VI
3rd-22nd August
1949
15°c
15°c
18°c

Figure 7 (*cont.*).



Distribution of *Carinaria lamarki.*

SUMMARY.

The distribution of Pterotracheidae and Carinariidae is described throughout a period of one year over an area extending from 27° N. to 47° N. within 500 miles of the North American coast. *Pterotrachea scutata*, *P. minuta*, *P. coronata* and *Firoloidea desmeresti* all occur within this area, but are relatively rare. *Pterotrachea hippocampus* is more common, but occurs only in the southern part of the area; it is possible that all these species occur in greater numbers below 27° N. *Carinaria lamarki* was the only carinariid collected and was common between 30° N. and 40° N. In this species spawning takes place mainly in early spring. There is a sudden and almost complete disappearance of individuals in the autumn; this and some other aspects of the biology of this species are discussed.

REFERENCE.

TESCH, J. J. (1949). Heteropoda. *Dana Report, Copenhagen.* No. 34.

ransactions, American Geophysical Union   Volume 33, Number 4   August 1952

THE REFRACTION OF GROUPS AND OF THE WAVES WHICH THEY GENERATE IN SHALLOW WATER

E. Allan Williams and John D. Isaacs

(Contribution from the Scripps Institution of Oceanography, New Series, No. 580)

Abstract--A process is described which may be of importance in beach and near-shore development and which may account for surging in the surf zone as well as other phenomena. It is shown how a group front may be refracted according to one law as it approaches a coast and then, after reflection, proceed seaward under quite a different law. This permits the outgoing wave to move in a direction that it could not ordinarily attain, and causes "trapping" under many conditions. Stoneley's theory of refraction of energy fronts is further developed to permit quantitative investigation of group refraction on various types of shores. On the basis of the assumed hypothesis, the outgoing surf beat may be totally reflected from deep water, then reflected from the beach, a process which can occur repeatedly and result in newly arriving groups with variable phase relationships. Theory and techniques are developed for the investigation of the surf-beat path. The refraction of the reflected groups is shown to display regions of high convergence, divergence, and reinforcement.

Introduction--The variability of the swell and wind waves upon a coast imparts a complexity their refraction and to the resultant processes of shore and offshore transport. Further in-estigation and analysis will be required before this complexity is fully understood.

A typical train of waves consists of a number of crests which are relatively consistent in riod but variable in height. The variation in height takes the form of groups of higher waves arving at intervals of one to four minutes. As such a train enters shallow water, the individual ase crests are refracted, converging on ridges and shoals, and diverging over basins and canyons. e refraction of these crests has been much studied, but all such studies have considered only the ase refraction [U. S. HYDROGRAPHIC OFFICE, 1944; MUNK and TRAYLOR, 1947; JOHNSON, BRIEN, and ISAACS, 1948].

The refraction of the group, however, is quite different from that of the individual phase crests. hereas the phase velocity decreases continuously as the water shoals, the group velocity first ineases, reaching a maximum at a depth of h/L_0 (or d/L_0) equal to 0.157, and then decreases conuously for water shoaler than this. As a consequence of these velocity relationships, the group ont in the initial phase of refraction increases its angle to the contour, while the phase wave-ont angle diminishes. In the final stage of the group refraction the angle to the contour decreases t remains considerably greater than the corresponding phase wave angle. Therefore, when this fraction takes place over a gradually sloping bottom, the group or energy front will be curved so at it crosses several phase wave crests. Each phase wave will partake of the higher energy assoated with the mid-portion of the group at the point of crossing, which will cause it to have greater an normal height for some distance along its crest. Thus an echelon pattern should result as dissed by STONELEY [1935] and ISAACS, WILLIAMS, and ECKART [1951]. This may frequently acunt for the early short crests of waves approaching the shore.

As the waves of a group break at the shore, they cause the water level to vary in height with a riod of one to four minutes. Outgoing waves generated by this fluctuation in height have been signated "surf beat" by MUNK [1949]. In many instances, as a result of group refraction, the ergy front approaches the shore at an angle much greater than that of the phase wave. The fluction of water height will then be expected to progress along the beach in step with the arrival of energy front. Under these conditions the surf-beat wave would proceed, not directly outward m shore, but along a curved ray path which is dependent upon the direction and characteristics the incoming waves, and upon the refraction which they have experienced. Graphical construcns and analysis indicate that in most cases at a straight beach with parallel contours, and in me other situations as well, the surf-beat ray curves, becomes parallel to the shore at some ximum depth, and then returns to shore. Moreover, this phenomenon of total reflection from p water [ISAACS, WILLIAMS, and ECKART, 1951] may be accompanied by reflection from the ore, with the result that a wave experiencing such alternate multiple reflection can be propagated eat distances along a coast line.

The surf beat which is totally reflected from deep water can return to the shore either in or out of phase with the energy front of an incoming group. This interference will cause added vari tion in the water level at the shore line both above and below normal. The exaggerated surging noted in open bays may be the result of a condition of resonance between the incoming group, which provides the force of excitation, and the natural frequency of the surf-beat oscillation in it travel from the region of generation, reflection from deep water, and return to the shore.

The study of the mechanisms associated with the phenomena described above is presented in two parts; first, the treatment of the incoming group refraction by application of principles developed by Stoneley, and second, the development of techniques and theory for the investigation o the surf-beat path.

Group refraction of surface gravity waves--The general theory of the refraction of a wave group as developed by STONELEY [1935] can be applied to the graphical construction of group re fraction diagrams and, where bottom topography permits, to analytical determinations. The ener between two phase-wave orthogonals is presumed to remain constant and to travel with the group velocity, C_G. Accordingly, an element of the energy front advances with group velocity, not nece sarily normal to the energy front, but normal to the phase-wave front through the element in ques tion; that is, along the phase orthogonal through the element.

If the water is deep or of constant depth, the energy front advances so that lines representing its successive positions are parallel. The distance between two successive positions in this case will be proportional to $C_G \cos \psi$ (as shown at the right of Fig. 1), where ψ is the angle which the energy front makes with the phase-wave crest, while the distance which an element moves alo a phase-wave orthogonal is proportional to C_G. In general, the angle α between the phase-wave front and the refracting boundary may be either larger or smaller than ϕ, but for deep-water waves which have entered shallow water ϕ exceeds α. In deep or constant depth water the angle ψ between the two fronts will remain constant. When phase waves are refracted, however, the energy or amplitude front likewis is refracted. Suppose the orthogonals of a phas wave refraction diagram to have been drawn an the initial position of an energy front determine The change in position of a given element of the energy front can be established by advancing th element a distance proportional to the group ve locity, C_G, along the phase-wave orthogonal through the element. The positions of the elements thus obtained are joined to form the advanced energy front. Energy fronts so obtained cannot be thought of as a representation of simu taneous positions of different group crests as i the case of phase-wave crests, but only as repr senting the advance with time of an individual energy front. Techniques similar to those used in construction of the usual phase-wave refraction diagrams can also be applied in the case of group refraction.

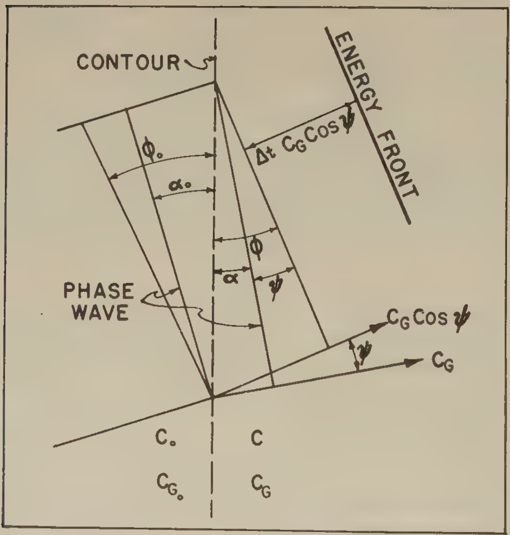


Fig. 1--Refraction of phase wave and energy front; advance of energy front in water of constant depth

The special case of refraction of a group over a straight beach with parallel contours has bee examined by analytical methods. The expression for the angle between the energy front and conto line for this condition can be obtained from the relation given by Stoneley for refraction of the energy front. His expression, which becomes

$$\sin \phi_0 / C_{G_0} \cos (\phi_0 - \alpha_0) = \sin \phi / C_G \cos (\phi - \alpha) \ldots \ldots \ldots \ldots (1)$$

for progression from deep to shallow water, gives the general relationship between energy fronts before and after refraction (see Fig. 1). Using this equation and Snell's law for phase-wave refrac tion and taking $\phi_0 = \alpha_0$ one obtains the equation

$$\phi = \cot^{-1}\left\{[1 - 2 (C/C_o)(C_G/C_o) \sin^2 \alpha_o]/2 (C_G/C_o)(\sin \alpha_o)(\sqrt{1 - (C/C_o)^2 \sin^2 \alpha_o})\right\} \ldots (2)$$

where ϕ is the angle which the energy front makes with the contour, C is the phase velocity and C_G the group velocity at the contour, C_o is the deep-water phase velocity, and α_o is the initial leep-water angle between the wave front and the contour.

Diagrams have been constructed for a straight beach with uniform slope to determine the refraction of the energy front. This requires that phase-wave orthogonals or rays first be drawn. Energy fronts and phase-wave rays are indicated in Figure 2 for 14-sec phase waves, for which

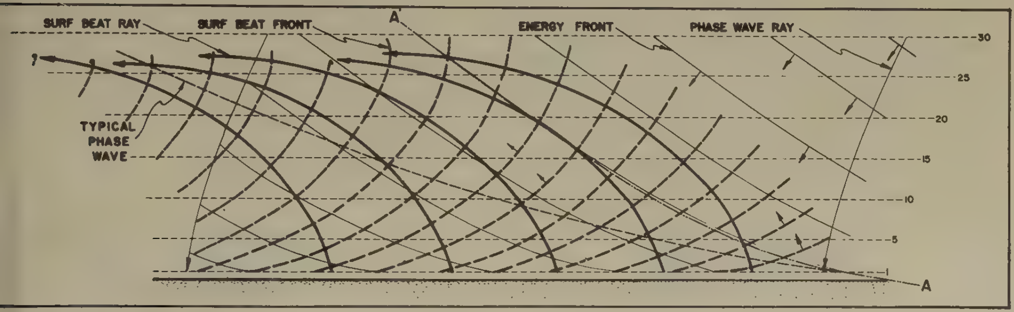


Fig. 2--Refraction of waves generated by incoming wave groups in the surf zone along a hypothetical straight beach of uniform slope; waves are totally reflected by deep water; a representative phase wave is shown; the group front AA′ was constructed from analytical data

α_o = 30°, approaching a straight beach of 4.25 pct slope. The time interval of advance for the nergy front is twice the phase-wave period. The angle between the phase-wave crest and the ontour continuously decreases as the wave progresses from deep to shallow water. However, he corresponding angle for the energy front increases from its initial value of 30° to about 36° t a depth of 25 to 30 fm and then decreases rapidly to approximately 11° at one fathom. The orresponding values of α for the phase waves are 25° and 5 1/2° respectively. In the advance nto shallow water the group velocity exceeds 1/2 the phase velocity and is even greater in this egion than in deep water; hence an initial increased energy-front angle to the contour is obtained. 'he line (AA′) is a refracted energy front constructed by use of data from (2). In view of the generally accepted inaccuracies of graphical refraction diagrams, the agreement between the graphcal and analytical constructions is remarkable.

In Figure 3 is shown a group refraction diagram for the irregular bottom north of La Jolla. 'he phase-wave refraction diagram, designated as Figure 8 of MUNK and TRAYLOR [1947] for 4 sec from WNW, was made available and has been used as a basis for the construction. The ifference in the refraction patterns results in the formation of phase and group fronts of opposite urvature as evidenced in the region of the three representative phase crests shown in the figure. t La Jolla Cove, where the phase orthogonals converge, the group fronts approach a parallel retion to the orthogonals. This is apparently the manner in which the group-refraction diagram ndicates regions of convergence. North of the canyon the phase waves and group fronts approach e shore practically parallel to each other. It is seen that, far from simplifying the problem of efraction, this application shows it to be even more complex than phase-wave refraction diagrams ave indicated.

Refraction of long-period waves--MUNK [1949] in his investigation concluded that the shore ne acts as a radiating line source which returns approximately one per cent of the incoming wave ergy in the form of long-period (two-to-three minute) waves termed surf beat. He correlated e height oscillations with the variability of water transport into the surf zone by studying the adance of groups of waves over wave and tsunami recorders at Scripps Pier. TUCKER [1950] has easured long sea waves with periods of two to three minutes, shown them to be the result of the rying height of groups of waves breaking on the shore, and discussed the mechanism by which ey are produced. Such a study at a point along the shore could be carried out without consideraon of group refraction.

The investigation of the path of a surf-beat wave, however, assuming it to be generated at the ore by an incoming group, requires (1) the determination of the effect of group refraction upon e incoming energy front, and (2) the effect of refraction upon the surf beat itself. The advance of

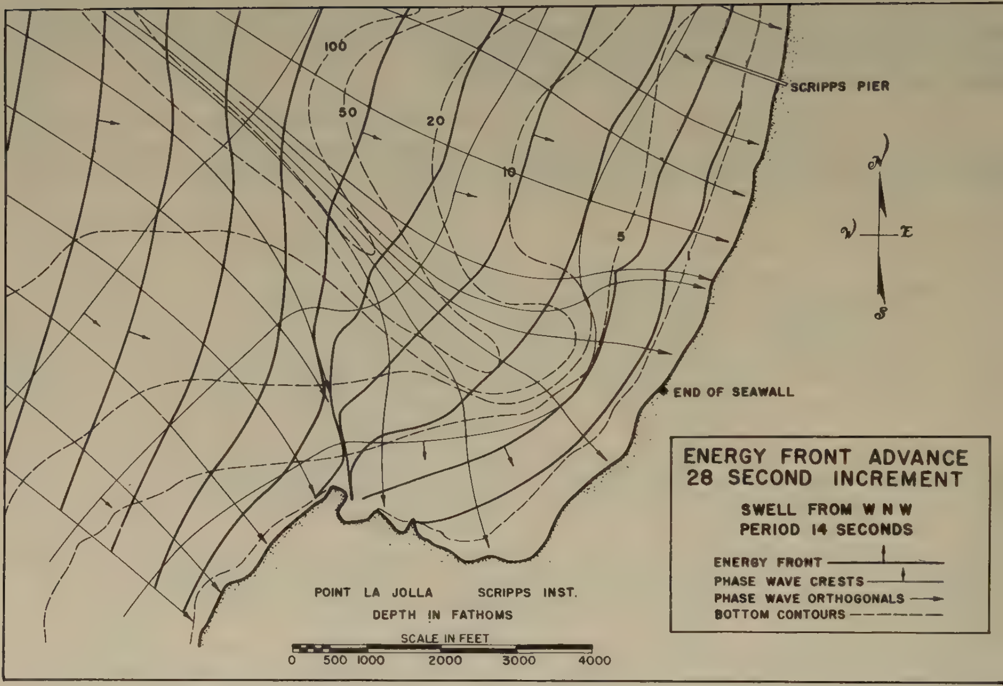


Fig. 3--Graphical energy-front refraction construction for the Point La Jolla - Scripps Institution region

the generating source along the beach is determined by the character and initial direction of the incoming waves, and the effects of bottom topography upon the refraction of the group. The init direction of the surf beat is determined by these conditions also. The seaward return of the lon period waves generated in this manner at the shore and the resultant total reflection from deep water is considered below. Graphical techniques have been used for the most part, although the special case of a straight beach with uniform slope has been treated analytically and found to be source of generation of long-period waves, most of which exhibit the interesting phenomenon of total reflection from deep water.

The outgoing wave-front positions were established from the application of wave generation in accordance with Huygen's principle, assuming the one-fathom contour to be the line of gener tion. Thereafter, a given wave front was formed by joining points obtained through the advance each element a distance, based upon $\sqrt{gh}$ as the velocity of propagation, along the direction of t normal to the wave front. If this velocity is compared with the velocity of the incoming group n shore, it is found that the two velocities approach equality for values of h/L_0 less than 0.006. cordingly, an energy front may be considered as partially reflected, in accordance with the laws regular reflection, at some convenient depth within this limitation. This has been the assumpti in the analytical approach. However, there must also be a practical lower limit of h/L_0 at whic either method may be applied, since the laws upon which the refraction is based may not hold a the waves break.

The graphical determination of the surf-beat path for one set of conditions in the region of Scripps Institution is shown in Figure 4. For convenience in studying the diagram, the positions of the wave fronts have been marked by letters. The energy-front positions are designated by small letters, and those of the outgoing wave by capitals. Simultaneous locations are indicated the same letter. The letter designations begin with a and A as the point at which the energy fr first reaches the one-fathom mark. The time increment is 28 sec except where complexity re quires advance by intermediate steps, such as E′ and E″ between E and F at the head of Scripps Canyon.

The surf beat below the Point, as shown by the front advance A to H, returns seaward to dee water. North of Scripps Pier at the head of Scripps Canyon the refraction, though complex, can

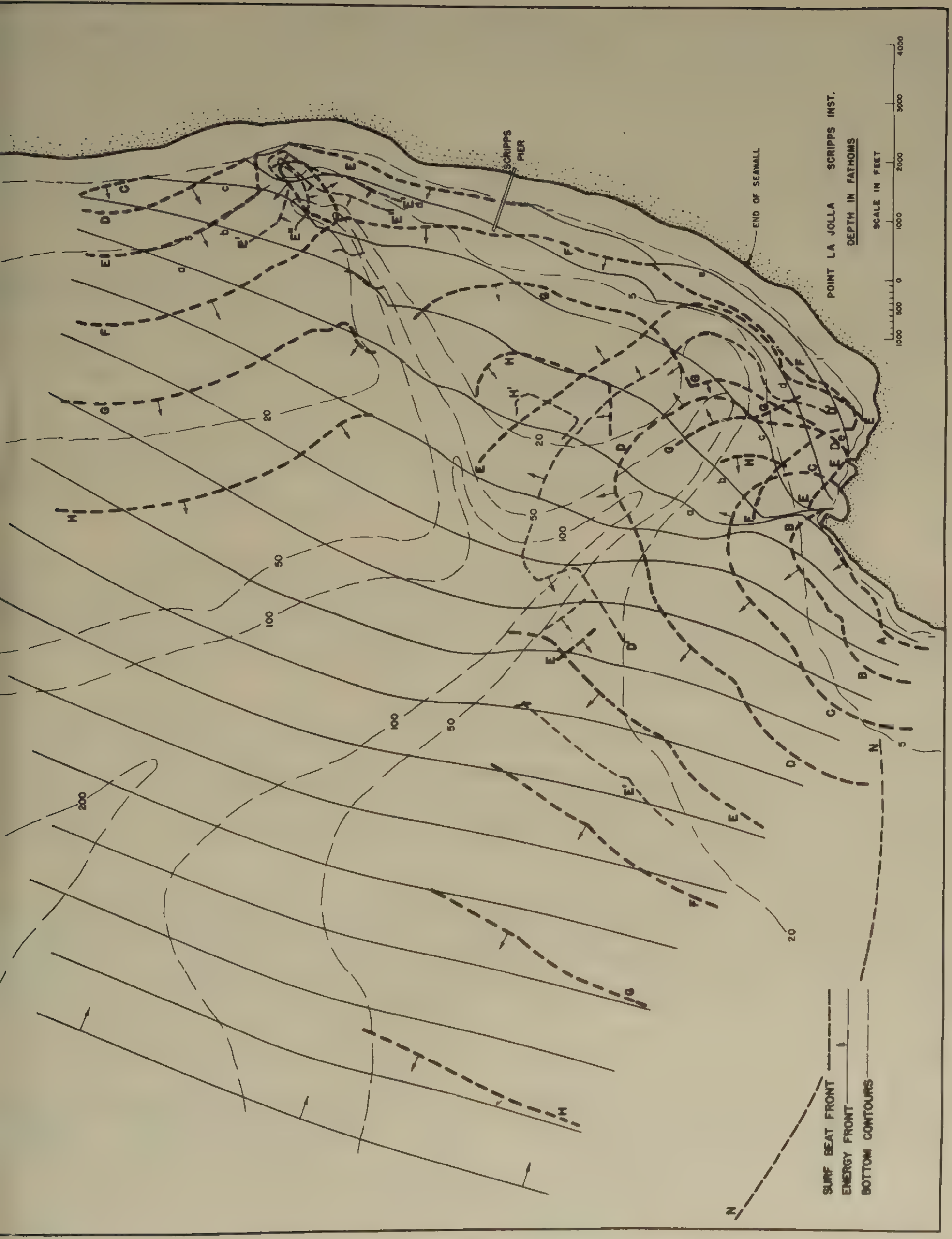

POINT LA JOLLA   SCRIPPS INST.
DEPTH IN FATHOMS
SCALE IN FEET
1000 500 0 1000 2000 3000 4000
END OF SEAWALL
SCRIPPS PIER
SURF BEAT FRONT
ENERGY FRONT
BOTTOM CONTOURS
5
20
50
100
200
A
B
C
D
E
E′
E″
F
G
H
H′
N
a
b
c
d

Fig. 4--Refraction of waves generated in the surf zone by wave groups, Point La Jolla - Scripps Institution

be followed with some measure of certainty. Beginning at the wave front E, a 14-sec inter-
ate step (E′-E′) is shown. Arrows indicate that the wave is moving to cross the canyon from
side. Seven seconds later (E″-E″) the two segments have almost met, while at the end of
ull 28-sec increment (F-F) the "loop" over the head of the canyon has been completed. The
fronts advancing from each side have crossed the canyon and are continuing as indicated.
this is a region of high energy, there must be considerable dissipation in this action. The
nce down the canyon from the "loop" crossing is difficult to determine, but the segments
n represent an estimate of the probable positions. If it is assumed that the velocity of progress
is $\sqrt{gh}$, then the extreme steepness of the canyon walls effectively introduces discontinuities,
at a continuous wave front extending across the canyon cannot be maintained.

In the area between La Jolla Point and the Canyon the diagram is more complex than at t head of Scripps Canyon, but the resulting forms are somewhat similar. The surf-beat advanc BCDD′E here is northeastward over the head of La Jolla Canyon and toward the beach. The f E approaches the shore at the south end of the sea wall almost coincident with the arrival of t energy front "e" which has progressed directly over the canyon. The front F is generated by direct incoming energy front, and develops into G as a "loop" or cross. The arrows aid in fo ing the diagram. The construction is not carried further for this section, but it can be seen t as the two sections of G cross over, one approaches shore to the east, while the other procee toward the Point. Between the two canyons the wave FGHH′, which progresses over the comp tively uniformly changing bottom, refracts from G to H, and finally, owing to greater velocitie the extremities, appears to almost reach a focus in the region H′.

The wave front to the north of Scripps Canyon is shown by steps C through H. Here the c tours are quite regular, and the wave appears to be directed toward the open sea. Due to the culiar topographic features, however, the wave undergoes great divergence. Of the step-by-s advance I to N, only the wave front position N at the bottom of the page has been reproduced. section N represents only a small portion of the initial wave front. Actually, the upper portio H proceeds seaward almost due west, while the inner part of the front N returns to the shore ginning at a point along the beach below and off the figure. The energy of the wave is thus spr between these two limits. The return of the surf beat to the shore should have comparatively little effect upon water height because of the marked divergence in this instance, but is impor in that it demonstrates a mechanism of interference. A similar return of the surf beat, but u conditions of convergence, could have a profound effect upon height variation.

This graphical study demonstrates that for the incident waves studied some of the long-pe waves return to the sea, while some after development and refraction are directed back towar shore. In the areas of phase-wave convergence the energy front and the outgoing waves are v complex. The energy is high in these regions, but in view of the high dissipation over the can heads, there is no definite indication of a pattern of interference which might produce waves o excessive magnitude sweeping out a canyon.

The surf-beat front assumed to be generated by an energy front at a straight beach with u form slope is shown in Figure 2. The rays obtained indicate that this wave does not proceed i definitely toward deep water, but reaches a maximum depth or distance from shore. It may be ticipated that these rays return shoreward, but the graphical construction does not provide a n of continuing the paths beyond maximum depth. However, this situation permits of analytical t ment, given below, which does give rise to the important case of "total reflection" from deep as a result of the wave refraction.

Since the analytical development for this special case treats both the incoming group and ray path of the long-period wave generated at the shore line, without recourse to graphical me it provides a check upon the graphical method of construction. Although there is some deviati from one construction path to the next, they are, on the whole, quite similar in form to the ray which has been obtained analytically. The average maximum depth of 27 fm obtained graphica compares favorably with the value of 27.7 obtained from analytical computation. This result i much better than could be expected in the case of a complex diagram such as Figure 4.

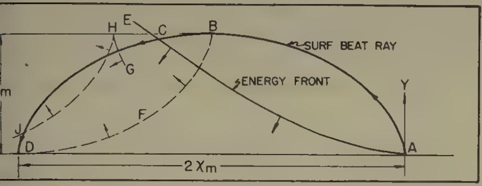
Analytical determination of the path of a wave generated by the energy front at a straight beach of uniform slope--The analytical description of the path of a wave group as it approache straight beach of uniform slope has been given above. Assuming that this group or energy fro generates a long-period wave as it traverses the beach, let us now consider the analytical description of the path of this newly formed wave as it progresses seaward. This path can be expressed in terms of the characteristics of the incoming phase waves and the slope of the beach

The analytical treatment of this problem by application of Fermat's principle of least trav time such as applied by ARTHUR [1946] is carried out by minimizing the integral

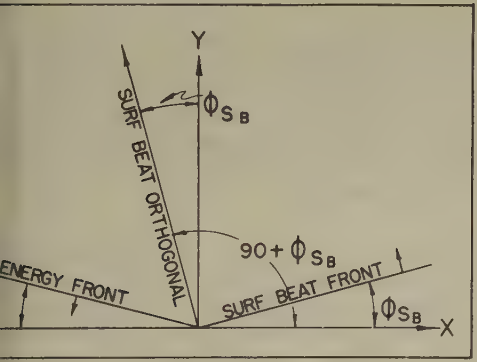
$$I = \int_{\text{path}} (1/c)\, ds = \int_{\text{path}} \left\{[1 + (y')^2]^{1/2}/(gay)^{1/2}\right\} dx \;\ldots\ldots\ldots\ldots\ldots$$

where ds is an element of the path, c the velocity of the disturbance, y′ equals dy/dx, and ay is depth h, a being the slope. The coordinate x is parallel to the shore and y positive outward as shown in Figure 5. A solution of this equation [JOOS, 1934, p. 71] is

$$(ay)\,[1 + (y')^2]\,K = 1 \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$



g. 5--Path of surf-beat wave generated along a straight beach of uniform slope as determined analytically



g. 6--Diagram of energy front and surf-beat front at the line of generation

where K is a constant which can be determined either graphically or analytically. From the graphical construction of the ray

$$K = 1/\left\{ay_1 \left[1 + (y_1')^2\right]\right\} \ldots\ldots\ldots (5)$$

where y_1' is the slope of the ray evaluated at some point (x_1, y_1). Analytically, K can be determined as a function of the constants related to the incoming waves as shown below.

An examination of (5) reveals that the maximum distance from shore which a ray reaches is

$y_m = 1/aK$ and the maximum depth $h_m = 1/K$ . .(6)

The solution of (4) in terms of x and y is

$$\pm x = -\sqrt{y/Ka - y^2} + 1/Ka \sin^{-1} \sqrt{Kay} \ldots (7)$$

where x = 0, y = 0 is some point at the shore line. When $y = y_m$

$$x = \pm (\pi/2)\, y_m, \pm(3\pi/2) y_m, \text{etc.} \ldots (8)$$

as a result of the multiple-valued function.

From the solution of the integral (3) the time t_m required for the disturbance to travel from $y = 0$ to $y = y_m$ is found to be

$$t_m = (2 \sin^{-1} 1)/(a\sqrt{gK}) \ldots\ldots\ldots (9)$$

ultiple-valued function associated with the corresponding x_m values. Therefore,

$$t_m = \pi/(a \sqrt{gK}) = \pi \sqrt{y_m/ag} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

The solution indicates a ray path such as ABCD, Figure 5, with x_m and y_m as shown. The t_m is the time required for the disturbance to traverse the arc AB or BCD, etc. ECA is the ming generating energy front. Let the point A be the origin x = 0, y = 0, and suppose the energy t to reach A at time t = 0. It will arrive at D when $t = t_m$, the surf-beat ray will reach B at the e time, and the outgoing wave front at that instant will be represented by BFD. The velocity $\sqrt{gh}$ is equal to the rate of progress of the generating front along the shore AD. A progressive wave nces parallel to the shore with this velocity.

The constant K has been evaluated in terms of incoming phase wave and group characteristics. gure 6 let the depth be sufficiently small, h/L_0 of 0.006 or less, so that the incoming group city C_G is practically equal to $\sqrt{gh}$, the velocity of the surf beat. The angle of the surf-beat ϕ_{SB} can then be set equal to the angle ϕ_h for the energy front. The value of the constant K bees

$$K = 1/(ay_1)\left[1 + (y_1')^2\right] = 1/h\,(1 + \cot^2 \phi_h) \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

e $\phi = \phi_h$ is to be evaluated at some depth h determined by the relation $h/L_0 = 0.001$. (The seon of depth h corresponding to this value of h/L_0 is a choice of convenience. A consideration e velocity relations and of the depth at which breakers are formed seems to indicate that a onable value for h/L_0 should be between 0.001 and 0.006.) By use of (2) the computation, upon duction of simplifying approximations, yields

$$K = (50.0\,\pi \sin^2 \alpha_0)/(g\,T^2) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

e T is the incoming wave period. Therefore, from (10)

$$t_m = \pi/a\sqrt{gK} = 0.251\, T/a \sin \alpha_0 \ldots\ldots\ldots\ldots\ldots\ldots (13)$$

If in use of (13) we consider a given beach, the slope a is constant, and for any given deep-water direction sin α_0 is also constant, while $t_m = AT$ indicating a linear relation between t_m and T. A family of straight lines relating t_m and T for specified values of α_0 can be drawn. B use of (10) the values of h_m, x_m, y_m, are readily plotted on the t_m axis. Values of h_m, y_m, anc t_m are readily obtained from such a plot. The results for such a hypothetical beach should pro useful as a guide in estimating similar relations on actual beaches which possess some measur of regularity.

Discussion and conclusions--The agreement in the special case of a straight beach with un form slope, between the energy front as obtained analytically and that obtained by graphical me provides support of the graphical construction in cases where the analytical approach is difficul or impossible. Except in the situations where the phase-wave orthogonals approach very close each other, no difficulty is encountered in the graphical method. The diagram for waves approa ing a straight uniform beach from an angle indicates the formation of an echelon pattern of shor crested waves from long-crested swell.

The energy of the surf beat generated by the group front appears to be largely dissipated in regions of complex bottom topography such as exists in the vicinity of submarine canyons. How ever, along a straight beach which possesses a reasonable degree of uniformity it seems probal that the energy front due to waves initially at an angle to the contours will generate surf beat wl gives rise to a progressive wave motion that will keep in step with the progress of the energy f the velocity being $\sqrt{gh_m}$. If such a progressive wave is reflected by a discontinuity such as a shallow bar or breakwater, the conditions for standing waves, their axes parallel to the beach, a met.

The surf-beat ray paths produce a caustic with the resulting formation of standing waves, their axes normal to the beach, as discussed by ISAACS, WILLIAMS, and ECKART [1951]. The mathematical relationships of this standing-wave formation, which have been investigated by Eckart, will be reported by him in the near future. The ray treatment used here leads to the un tenable requirement of infinite wave height (see H, Fig. 5) in the case of a caustic. Actually, as in the case of total reflection of light [JOOS, 1934, p. 343] it will be expected that some disturba exists beyond h_m, the depth given by the ray treatment for total reflection.

The ray path and travel time obtained in the case of a hypothetical straight beach of uniforn slope suggest the possibility of similar conditions in the case of an open bay where multiple reflections from the two sides may take place. If the period and direction of the incoming waves a such that the "group period" is equal to this travel time or an appropriate sub-multiple thereof this resonant condition may well be the explanation, not only of excessive surging but also of the variations in the height of the surges.

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FIGS. 1–9, SEPTEMBER, 1952

MEASURES FOR DESCRIBING THE SIZE DISTRIBUTION OF SEDIMENTS[1]

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ABSTRACT

Numerous measures are used in the literature to describe the grain-size distribution of sediments. Consideration of these measures indicates that parameters computed from quartiles may not be as significant as those based on more rigorous statistical concepts. In addition, the lack of standardization of descriptive measures has resulted in limited application of the findings from one locality to another.

The use of five parameters that serve as approximate graphic analogies to the moment measures commonly employed in statistics is recommended. The parameters are computed from five percentile diameters obtained from the cumulative size-frequency curve of a sediment. They include the mean (or median) diameter, standard deviation, kurtosis, and two measures of skewness, the second measure being sensitive to skew properties of the "tails" of the sediment distribution. If the five descriptive measures are listed for a sediment, it is possible to compute the five percentile diameters on which they are based (ϕ_5, ϕ_{16}, ϕ_{50}, ϕ_{84}, and ϕ_{95}), and hence five significant points on the cumulative curve of the sediment. This increases the value of the data listed for a sediment in a report, and in many cases eliminates the necessity of including the complete mechanical analysis of the sediment.

The degree of correlation of the graphic parameters to the corresponding moment measures decreases as the distribution becomes more skew. However, for a fairly wide range of distributions, the first three moment measures can be ascertained from the graphic parameters with about the same degree of accuracy as is obtained by computing rough moment measures.

INTRODUCTION

Numerous descriptive measures obtained from the grain-size analysis of sediments are used in the literature to indicate the salient features of the size-frequency distribution of a sediment. These measures range in complexity from those obtained by computing the various moments[2] of the sample distribution about some central measure of sediment diameter, to those obtained by selecting a few points from the cumulative frequency curve of the sediment. The latter include such measures as the Trask coefficients of sorting and skewness, and Kelley's quartile kurtosis.

One of the fundamental purposes in listing sediment parameters is to facilitate the comparison of sediment analyses and to aid in the correlation between sediment types and their environment. There may be special studies for which standardization of descriptive parameters is not warranted; however, in general the use of widely divergent systems has markedly lessened the value of many sediment studies. For example, a worker who wishes to compare his findings with those of other workers is virtually limited to those studies employing the same or comparable parameters. Also, the significance of some works has undoubtedly suffered from the use of parameters that are not truly "relevant."[3] Since the field of sedimentation is expanding rapidly, this may be an opportune time to briefly review procedures now in use and make suggestions for standardization of the descriptive measures to be used in sediment work.

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[1] Contribution from the Scripps Institution of Oceanography, New Series No. 581. This work represents in part research carried out for the Beach Erosion Board and the Office of Naval Research under contract with the University of California.

[2] Discussion of moment measures is included in the appendix.

[3] Otto (1939) defines relevant parameters as numerical values which contain the essential information in a mechanical analysis.

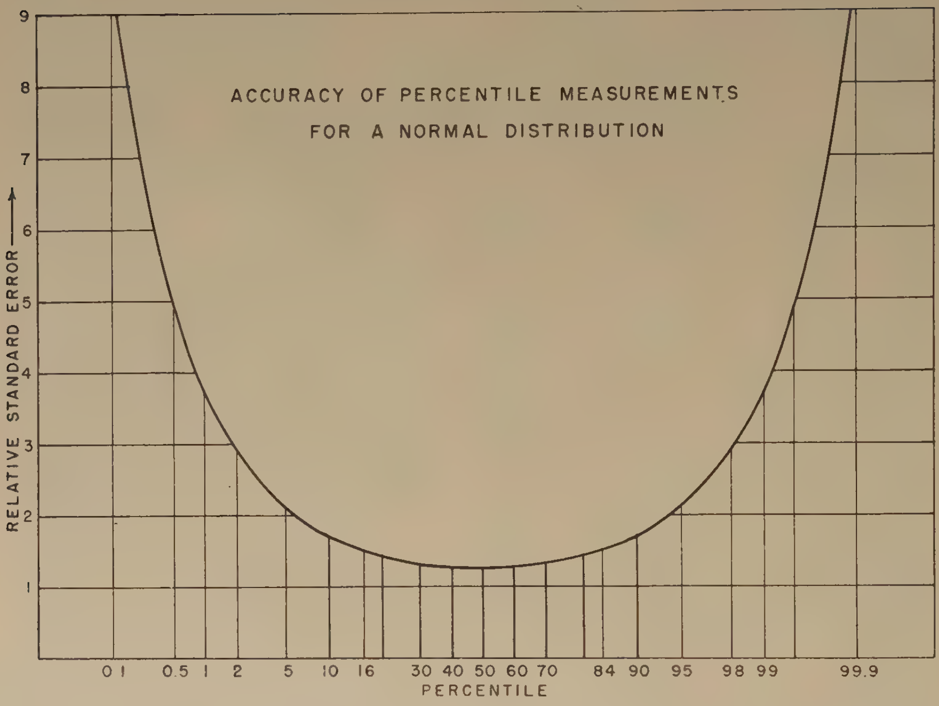

FIG. 2.—Showing the influence of fluctuations of sampling on the accuracy of various percentile measurements for a normal distribution. Note that errors are greatly increased for per centiles below 5 and above 95. (The ordinate of this curve is the relation $\sqrt{pq}/y_p$ which is derived in Yule and Kendall (1948), p. 382, equation 20.1. The true standard error for a given sample is the product of this quantity and $\sigma/\sqrt{n}$, where σ is the standard deviation of the sample, and n the number of observations.)

sorting of the sediment distribution. Thus distributions having the same value of quartile skewness coefficient do not have the same skewness values (as obtained by moment measures, for example) *unless* they have the same sorting. This will be discussed further in the section on measures of skewness.

Other measures such as Baker's (1920) equivalent grade and grading factor and Niggli's statistical parameters have also been widely used (see Krumbein and Pettijohn, 1938, pp. 255–257). A possible disadvantage of these measures is that it is necessary in computing them to use, for the independent variable, a diameter scale which is arithmetic in the millimeter notation. This scale results in pronounced skewness of the grain-size distribution which is reflected in the measures. For example, the measure of central tendency, the equivalent grade, is the arithmetic mean diameter in millimeters of the distribution, and because of this arithmetic character may not be as significant as a logarithmic measure of central tendency (Krumbein, 1936a, p. 37). In addition, the calculation of these parameters requires the use of a planimeter and is lengthy.

In a normal frequency distribution curve approximately 68 per cent of the population occurs between plus and minus one standard deviation to either side of the mean (or median, since these

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tively of a cumulative per cent (coarser) curve and $Md\phi$ is the phi median diameter.

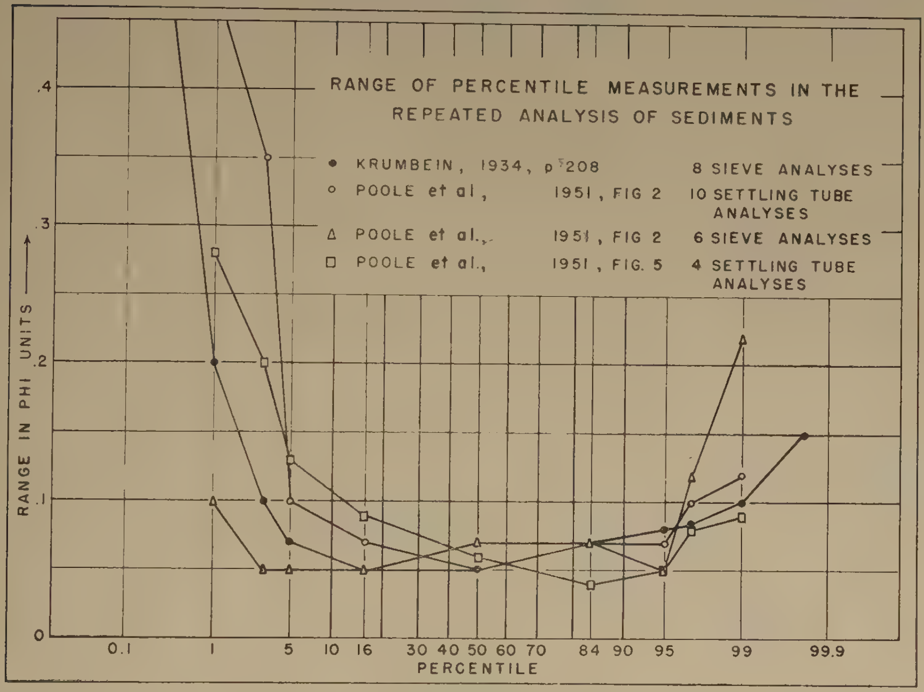

FIG. 3.—Range in phi units for various percentiles from the cumulative curves of repeated analyses of each of several samples. Note the wide range for percentiles less than 5 and greater than 95.

two measures are equal for a normal distribution), and 95 per cent occurs between two standard deviations either side of the mean. Thus the 16th and 84th percentiles of a normal sediment cumulative frequency curve represent diameters one standard deviation either side of the mean, and the 2½ and 97½ percentiles represent diameters two standard deviations either side of the mean.

Since many sediment distributions approximate a normal distribution or one of the family of curves derived from it, the use of percentiles based on standard deviations seems more meaningful for the description of size frequency distributions then those based on quartiles. However, before choosing definite percentiles for this description, the accuracy which can be obtained in the measurement of various percentiles in the size-distribution of sediments should be considered. From statistical theory it can be shown that the influence of fluctuations of sampling and analysis on percentiles increases away from the median (Yule and Kendall, 1948, p. 382). A curve showing the theoretical accuracy of percentile measurements for a normal distribution is shown in figure 2. The range in phi units for various percentiles from the cumulative curves of repeated analyses of each of several sediments is shown in figure 3. Inspection of these figures indicates that percentiles one standard deviation either side of the median (ϕ_{16} and ϕ_{84}) can be determined with almost the same accuracy as the median, and that there is appreciably greater inaccuracy in percentile measurements two standard deviations either side of the median ($\phi_{2\frac{1}{2}}$ and $\phi_{97\frac{1}{2}}$). However, the rerors in measuring the 5th and 95th percentiles are appreciably less than those

TABLE 1.—*Descriptive measures*

Measure		Nomenclature	Definition
Central Tendency	1*	Phi Median Diameter	$Md_\phi = \phi_{50} = M_\phi - (\sigma_\phi \alpha_\phi)$
		Phi Mean Diameter	$M_\phi = \frac{1}{2}(\phi_{16} + \phi_{84}) = Md_\phi + (\sigma_\phi \alpha_\phi)$
Dispersion (Sorting)	2	Phi Deviation Measure	$\sigma_\phi = \frac{1}{2}(\phi_{84} - \phi_{16})$
Skewness	3	Phi Skewness Measure	$\alpha_\phi = \frac{M_\phi - Md_\phi}{\sigma_\phi}$
	4	2nd Phi Skewness Measure	$\alpha_{2\phi} = \frac{\frac{1}{2}(\phi_5 + \phi_{95}) - Md_\phi}{\sigma_\phi}$
Kurtosis (Peakedness)	5	Phi Kurtosis Measure	$\beta_\phi = \frac{\frac{1}{2}(\phi_{95} - \phi_5) - \sigma_\phi}{\sigma_\phi}$
Diameter in Phi Units corresponding to a given percentage		5th Percentile Diameter	$\phi_5 = Md_\phi - \sigma_\phi + \sigma_\phi(\alpha_{2\phi} - \beta_\phi)$
		16th Percentile Diameter	$\phi_{16} = Md_\phi - \sigma_\phi + (\sigma_\phi \alpha_\phi)$
		50th Percentile Diameter	$\phi_{50} = Md_\phi$
		84th Percentile Diameter	$\phi_{84} = Md_\phi + \sigma_\phi + (\sigma_\phi \alpha_\phi)$
		95th Percentile Diameter	$\phi_{95} = Md_\phi + \sigma_\phi + \sigma_\phi(\alpha_{2\phi} + \beta_\phi)$

* In reporting data, it is sufficient to list only one measure of central tendency, since the second may easily be computed from the other parameters.

for the $2\frac{1}{2}$ and $97\frac{1}{2}$ percentiles. Further, it would be extremely difficult to obtain the $97\frac{1}{2}$ percentile diameter in the analysis of many fine-grained sediments. For these reasons, the 5th and 95th percentile diameters, obtained from the cumulative frequency curve, as used in this study as a working approximation to two standard deviations from the mean.[7]

Since descriptive parameters based on moments are too time-consuming for extensive application to sediments, and parameters obtained from quartile measures do not take into consideration a sufficient proportion of the total sample (i.e., in many cases they may not be "relevant parameters"), the most suitable compromise would seem to be the selection of parameters based on a graphic analogy to moment measures. Otto (1939) was one of the first to apply this concept to sediment distributions when he devised his modified logarithmic probability graph. He utilized the 16th and 84th percentile diameters to obtain a standard deviation, and the 4th or 96th percentile in calculating a measure of skewness. His method requires a special type of graph paper and the skewness term is only based on one end of the distribution.

The considerations discussed above have led to the selection of five parameters to describe the frequency distribution of sediments. These descriptive measures are defined in table 1, and are illustrated graphically in figure 4. Also, a simplified sheet for their calculation is

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[7] The 5th and 95th percentile diameters represent measurements 1.65 standard deviations either side of the mean in a normal distribution.

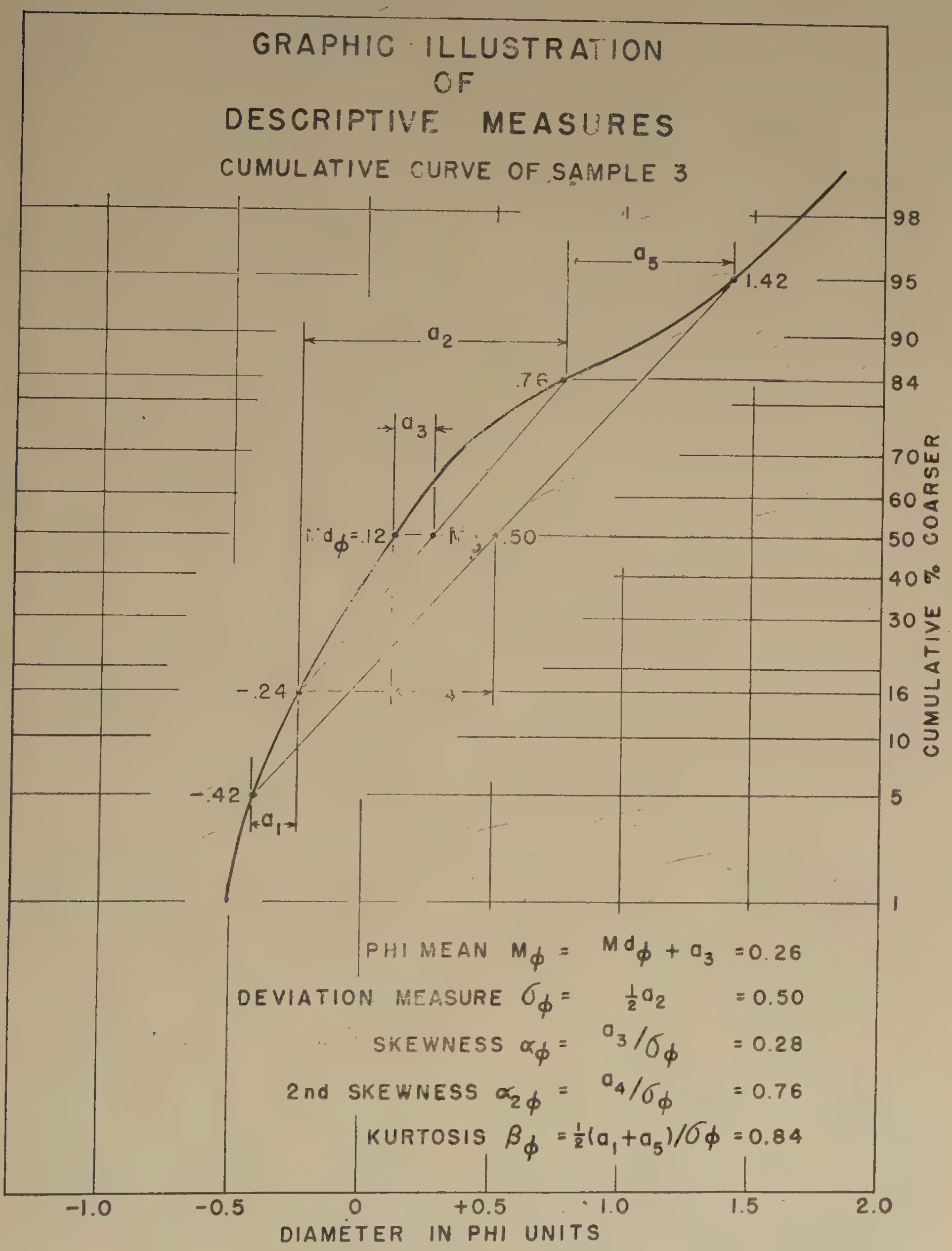

FIG. 4.

given in table 2, and a comparison of these parameters with those based on quartile measurements is given in table 3. The limits of accuracy, and the statistical basis of selection of the measures are discussed in the appendix. The measures

TABLE 2.—*Sample calculation sheet for the descriptive measures of sample 3*

Values of Md_ϕ, ϕ_{84}, ϕ_{16}, ϕ_{95} and ϕ_5 are obtained from the cumulative frequency curve shown in figure 4

Parameter notations are defined in table 1

$\phi_{84} = 0.76$	$\boxed{Md_\phi = 0.12}$
$\phi_{16} = -0.24$	
$\phi_{84}-\phi_{16} = 1.00\ (\frac{1}{2}) =$	$\boxed{\sigma_\phi = 0.50}$
$\phi_{84}+\phi_{16}\ \ 0.52\ (\frac{1}{2}) =$	$\boxed{M_\phi = 0.26}$
$M_\phi - Md_\phi =$	$\boxed{S = +0.14}$
$S/\sigma_\phi =$	$\boxed{\sigma_\phi = +0.28}$
$\phi_{95} = 1.42$	
$\phi_5 = -0.42$	
$\phi_{95}-\phi_5 = 1.84\ (\frac{1}{2}) =$	$K = 0.92$
$K/\sigma_\phi - 1 =$	$\boxed{\beta_\phi = 0.84}$
$\phi_{95}+\phi_5 = 1.00\ (\frac{1}{2}) =$	$M_2 = 0.50$
$M_2 - Md_\phi =$	$S_2 = 0.38$
$S_2/\sigma_\phi =$	$\boxed{\alpha_{2\phi} = +0.76}$

recommended in this study have been selected with the following points in mind:

1. The measures serve as approximate graphic equivalents to the moment measures commonly employed in statistics, and the notation is that generally used for analogous measures in statistics.
2. The parameters are based on five percentile diameters (ϕ_5, ϕ_{16}, ϕ_{50}, ϕ_{84}, and ϕ_{95}) obtained from a cumulative frequency curve of the sediment distribution. It is recommended that the cumulative curve be plotted on arithmetic probability paper (Hazen, 1914) since use of this paper results in a straight line plot for a normal distribution and thus facilitates curve fitting and visual interpretation of the data.
3. The measures are easy to visualize in terms of the sediment distribution (see figures 4 and 6), and are readily computed by subtraction and addition (see table 2).
4. Listing of the five measures gives the necessary data for computing five significant points on the cumulative frequency curve of the sediment (i.e., ϕ_5, ϕ_{16}, ϕ_{50}, ϕ_{84}, ϕ_{95}, see table 1) and thus in many cases will eliminate the necessity of reporting the complete mechanical analysis of the sediment.
5. It is recognized that some distributions may be adequately described by three parameters, a measure of central tendency, a measure of dispersion, and one of skewness. Also in some cases it may not be practical to measure percentile diameters as near the extremes of the distribution as the 5th and 95th percentile diameters. For these reasons the measures are selected so that distributions may be described by listing the three primary measures based on the 16th, 50th, and 84th percentile diameters. The primary parameters consist of a measure of central tendency (either the median or the mean), the phi deviation measure, σ_ϕ, and the phi skewness measure α_ϕ. These are somewhat similar in form to the phi quartile measures suggested by Krumbein (1936b), but have the advantage of being analogous to moment measures, and consider a larger percentage of the total distribution. However, whenever possible, five parameters should be listed, since they furnish a more complete description of the distribution.

Measures of Central Tendency—It is useful to be able to obtain both a median and a mean diameter since one may be more significant than the other for different studies. Both the phi median diameter, Md_ϕ, and the phi arithmetic mean

TABLE 3a.—*Comparison of descriptive measures in the phi notation based on approximate standard deviations with those based on quartile measurements*

Parameter	Sample Number			
	3	12	34	60
Phi Median Diameter, $Md_\phi=\phi_{50}$	0.12	2.25	3.78	3.28
Phi Mean Diameter, $M_\phi=\frac{1}{2}(\phi_{16}+\phi_{84})$	0.26	2.10	4.06	3.24
Phi Deviation Measure, $\sigma_\phi=\frac{1}{2}(\phi_{84}-\phi_{16})$.	0.50	0.51	0.74	0.41
Phi Skewness Measure, $\alpha_\phi=\dfrac{M_\phi-Md_\phi}{\sigma_\phi}$	+0.28	−0.29	+0.38	−0.10
2nd Phi Skewness Measure, $\alpha_{2\phi}=\dfrac{\frac{1}{2}(\phi_5+\phi_{95})-Md_\phi}{\sigma_\phi}$	+0.76	−0.81	+0.97	−0.23
Phi Kurtosis Measure, $\beta_\phi=\dfrac{\frac{1}{2}(\phi_{95}-\phi_5)-\sigma_\phi}{\sigma_\phi}$	0.84	0.83	0.96	0.57
Skewness Ratio, $R_\phi=\alpha_{2\phi}/\alpha_\phi$	2.71	2.79	2.55	2.30
Phi Quartile Deviation,[1] $QD_\phi=\frac{1}{2}(Q_{3\phi}-Q_{1\phi})$	0.30	0.31	0.42	0.28
Phi Quartile Skewness,[1] $Skq_\phi=\frac{1}{2}(Q_{1\phi}+Q_{3\phi})-Md_\phi$	+0.04	−0.07	+0.10	−0.01
Phi Quartile Kurtosis,[1] $K_{9\phi}=(Q_{3\phi}-Q_{1\phi})/2(P_{90\phi}-P_{10\phi})$	0.21	0.23	0.20	0.28

TABLE 3b.—*Descriptive parameters in the millimeter notation*[1]

Median Diameter, *Md* (mm)	0.92	0.21	0.073	0.103
Trask Sorting Coefficient, $So=\sqrt{Q_1/Q_3}$	1.23	1.23	1.34	1.22
Trask Skewness Coefficient, $Sk=\dfrac{Q_1Q_3}{Md^2}$	0.96	1.08	0.88	0.01
Kelley's Quartile Kurtosis, $Kq_a=(Q_3-Q_1)/2(_1P_{90}-P_{10})$	0.24	0.20	0.25	0.26

diameter, M_ϕ, may be obtained from the points selected from the cumulative frequency curve. They are defined as follows:

$$Md_\phi=\phi_{50}=M_\phi-(\sigma_\phi\alpha_\phi)$$

and

$$M_\phi=\tfrac{1}{2}(\phi_{16}+\phi_{84})=Md_\phi+(\sigma_\phi\alpha_\phi).$$

The phi deviation measure σ_ϕ, and the phi skewness measure, α_ϕ, are defined in table 1 and will be discussed in a later section. It should be noted that it is necessary to list only one of these measures of central tendency in reporting the descriptive parameters of a grain-size distribution because the other may readily be computed from the remaining parameters.

The median diameter is the 50th percentile diameter of a cumulative frequency curve, and thus may be obtained directly from the curve without interpolation. The median is less affected by extreme values of skewness because it is closer to the modal diameter than the mean. Therefore, the median would be a more useful measure of central tendency than the mean where the emphasis is on the more abundant size. On the other hand, the arithmetic mean can be manipulated algebraically, so that the average of the means of several samples will give the mean of the group. For example, consider a sediment sample which is composed of numerous laminae of equal thickness but having different grain-size distributions. For such a sample, the mean grain-size of the total sample is equal to the average of the means of the laminae, whereas the

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[1] Discussion of these parameters is given in Krumbein and Pettijohn (1938) pp. 230–238.

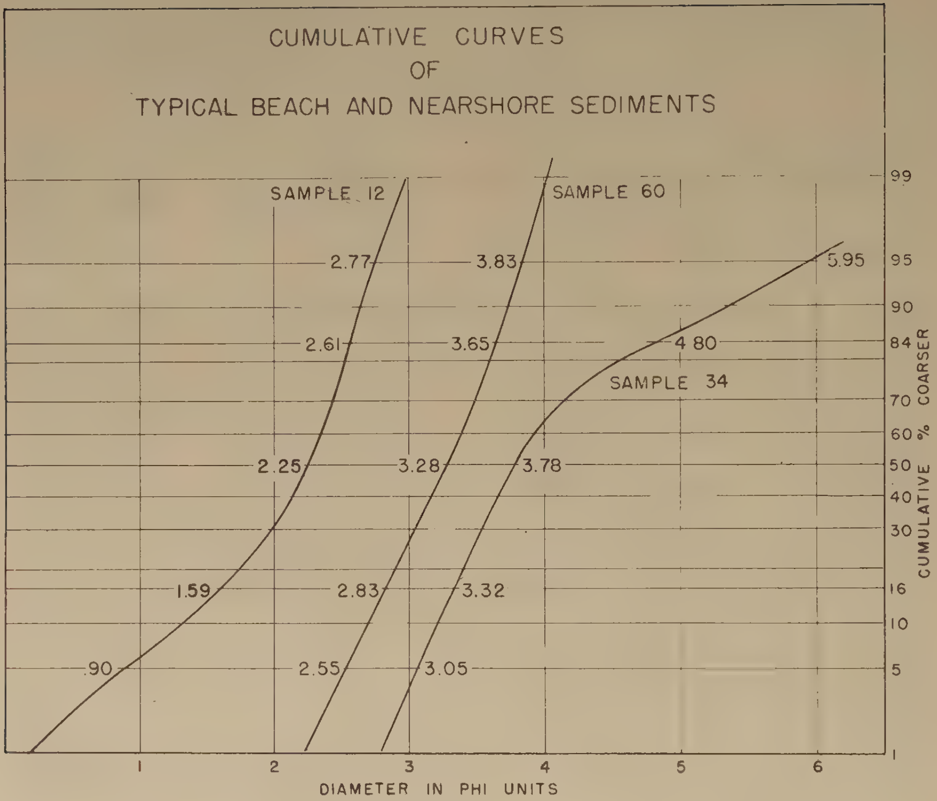

Fig. 5.

median of the total sample is not necessarily equal to the average of the medians of the laminae.

The measure of the mean recommended here is the average of the 16th and 84th percentile diameters and is essentially the same measure suggested by Otto (1939). This definition was selected because it is a good approximation to the mean obtained by moment measures for a large variety of distributions (compare the phi mean diameters of table 3a with the means obtained by moment measures given in table 5).

The mean and the median are equal in symmetrical distributions, but differ from each other in asymmetrical distributions. Geometrically, the median is the diameter value of the ordinate that divides the frequency distribution curve into two equal areas, while the arithmetic mean is the diameter value of the center of gravity of the frequency distribution (see figure 6). In this sense, the phi mean recommended here, M_ϕ, is arithmetic in that the independent variable of the frequency distribution curve is plotted in the arithmetic phi scale. With reference to the millimeter scale from which the phi units are derived ($\phi = -\log_2$ of diameter in millimeters), M_ϕ is a logarithmic mean. This follows, because if the phi scale of the independent variable were replaced by its equivalent in millimeters, the scale of the independent variable would become logarithmic. On the other hand, when converted to its diameter equivalent in millimeters, the

TABLE 4.—*Computation of the first four data moments of sample 12*[1]

(1) Class Limits, ϕ units	(2) Class Mark x_i	(3) f	(4) u	(5) uf	(6) u^2	(7) u^2f	(8) u^3	(9) u^3f	(10) u^4	(11) u^4f
<-1		.05	−6	− .30	36	1.80	−216	− 10.80	1296	64.80
-1 to $-\frac{1}{2}$	−0.75	.06	−5	− .30	25	1.50	−125	− 7.50	625	37.50
$-\frac{1}{2}$ to 0	−0.25	.49	−4	− 1.96	16	7.84	− 64	− 31.36	256	125.44
0 to $\frac{1}{2}$	+0.25	1.70	−3	− 5.10	9	15.30	− 27	− 45.90	81	137.70
$\frac{1}{2}$ to 1	0.75	3.70	−2	− 7.40	4	14.80	− 8	− 29.60	16	59.20
1 to $1\frac{1}{2}$	1.25	7.00	−1	− 7.00	1	7.00	− 1	− 7.00	1	7.00
$1\frac{1}{2}$ to 2	$x_0=1.75$	18.00	0							
2 to $2\frac{1}{2}$	2.25	45.00	1	45.00	1	45.00	1	45.00	1	45.00
$2\frac{1}{2}$ to 3	2.75	23.10	2	46.20	4	92.40	8	184.80	16	369.60
>3		.90	3	2.70	9	8.10	27	24.30	81	72.90
Totals		100.00		+71.84		+193.74		+121.94		+919.14
Moments about x_0			$v_1=+0.178$		$v_2=+1.937$		$v_3=+1.219$		$v_4=+9.191$	
Mean			$M=n_1=cv_1+x_0=2.11$ phi							
Moments about M			$m_2=c^2(v_2-v_1^2)=0.354$ $m_3=c^3(v_3-3v_1v_2+2v_1^3)=-0.277$ $m_4=c^4(v_4-4v_1v_3+6v_1^2v_2-3v_1^4)=0.827$							
Standard deviation			$\sigma=\sqrt{m_2}=0.59$ phi							
Skewness			$\alpha_3=m_3/\sigma_3=-1.35$							
Kurtosis			$\beta_2=m_4/\sigma_4=6.60$							

[1] The cumulative frequency curve for this sample is shown in figure 5 and the frequency distribution curve in figure 6.

TABLE 5.—*Descriptive parameters of sediments computed from moment measures, using phi notation and class intervals of* $\frac{1}{2}\phi$[1]

Parameter	Sample Number			
	3	12	34	60
Phi mean diameter, M	0.26	2.11	4.03	3.25
Standard deviation, $\sigma=\sqrt{m_2}$	0.51	0.59	0.88	0.41
Skewness, $\alpha_3=m_3/\sigma_3$	1.70	−1.35	2.08	−0.38
Kurtosis, $\beta_2=m_4/\sigma_4$	3.10	6.60	4.90	2.70

[1] In order to compute the moments for these open ended distributions it was necessary to assume a finite distribution. This accounts for some of the discrepancies between these parameters and their graphic equivalents listed in table 3a. In comparing these parameters with the graphic measures it should be noted that α_3 equals approximately $6\alpha_\phi$, and that when $\beta_2=3$, $\beta_\phi\doteq 2/3$ (see figure 9).

phi arithmetic mean becomes the geometric mean of the size distribution in millimeters.[8]

Measure of Dispersion (Sorting)—In the phi notation the standard deviation of a frequency distribution can be approximated graphically for many distributions by obtaining one-half the distance between the 16th and 84th percentile diameters on a cumulative frequency curve. The relation recommended

$$\sigma_\phi=\tfrac{1}{2}(\phi_{84}-\phi_{16})$$

was suggested for sediment studies by Krumbein (1938) and Otto (1939), and is referred to here as the phi deviation measure.

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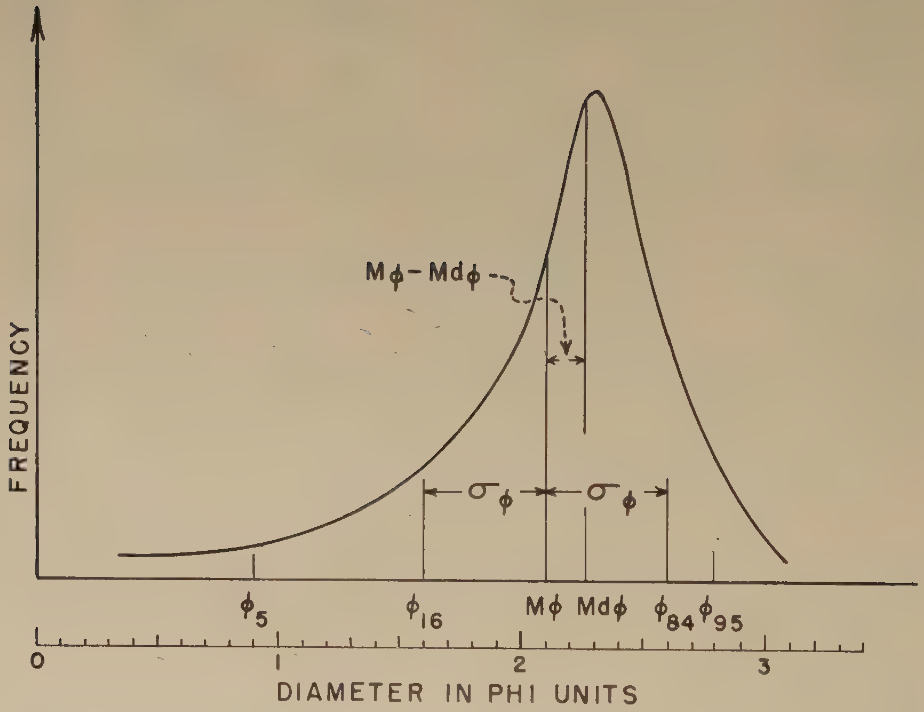
[8] This becomes more apparent if the antilog of the mean, $M_\phi=\frac{1}{2}(\phi_{16}+\phi_{84})$ is taken. The antilog of M_ϕ is $\sqrt{(P_{16})(P_{84})}$, where $P_{16}+P_{84}$ are the 16th and 84th percentile diameters in millimeters. This latter expression is obviously geometric. For further reference see Krumbein and Pettijohn, 1938, pp. 240–245.

FREQUENCY DISTRIBUTION CURVE OF SAMPLE 12



OBTAINED BY GRAPHIC DIFFERENTIATION OF CUMULATIVE CURVE USING THE METHOD OF KRUMBEIN AND PETTIJOHN (1938) PAGE 192.

FIG. 6.

The geometric significance of σ_ϕ is shown in figures 4 and 6. It will be observed, that the phi deviation measure gives the standard deviation of the curve in terms of Wentworth units, since one phi unit is equivalent to one Wentworth division. For example, samples 3 and 12 (table 3) have σ_ϕ values of approximately 0.5 phi, and hence the spreads of their distribution curves between the phi mean and the 16th or 84th percentile diameters are one-half of a Wentworth unit. Sample 34 has a σ_ϕ of 0.74, and thus its spread is approximately 1.5 times greater than that of samples 3 and 12.

In general the value of σ_ϕ deviates from the moment standard deviation as the distribution becomes more skew. The deviations from the moment standard deviation are discussed in the appendix (also see figure 8).

Measures of Skewness—In a symmetrical distibution the mean and the median coincide, but if the distribution is skewed the mean departs from the median, and the extent of this departure may be used as a measure of skewness. However, the skewness determined in this manner is not independent of the spread or deviation of the distribution. In order to secure an index that is independent of the spread of the curve, and thus may be compared with similar measures derived from other distributions, it is necessary to divide the departure of the mean from the median by the standard deviation of the distribution. The measure recommended is the phi skewness measure and is defined as follows:

$$\alpha_\phi=\frac{\frac{1}{2}(\phi_{16}+\phi_{84})-Md_\phi}{\sigma_\phi}=\frac{M_\phi-Md_\phi}{\sigma_\phi}.$$

This measure of skewness is related to the moment skewness, α_3, of statistics by the approximate relationship,[9] $\alpha_3=6\alpha_\phi$. The limitations to the phi skewness are discussed in the appendix.

The phi skewness measure is zero for a symmetrical size distribution. If the distribution is skewed towards smaller phi values (coarser diameters), the phi mean is numerically less than the median and the skewness is negative, (see figure 6). Conversely, α_ϕ is positive for distributions skewed towards higher phi values.

The sign of the skewness can be ascertained by inspection of the cumulative curve of the distribution. The mean of the distribution is given by the intersection of a straight line drawn between ϕ_{16} and ϕ_{84} with the 50 per cent line (see figure 4). If this point is greater than the median, the curve has a positive skewness. It should be noted that this straight line, drawn between the 16th and 84th percentiles on probability paper, represents a normal distribution having the same mean and standard deviation as the distribution under consideration, and that the value of the phi skewness measure gives, to the first approximation, the amount of the departure of the distribution from the normal.

The use of a secondary measure of skewness, called the second phi skewness measure, based on the 5th and 95th percentile diameters is also recommended. This measure has the same form as the primary skewness discussed above, and is defined as:

$$\alpha_{2\phi}=\frac{\frac{1}{2}(\phi_5+\phi_{95})-Md_\phi}{\sigma_\phi}.$$

The significance of this measure can be illustrated graphically by constructing a straight line between ϕ_5 and ϕ_{95} (see figure 4). In this case the straight line represents a normal distribution, having the same spread between the 5th and 95th percentile diameters as the curve under consideration. Thus $\alpha_{2\phi}$ is another measure of the departure of the curve from a normal distribution.

While the primary skewness measure α_ϕ is sensitive to skew properties occurring in the bulk of the grain-size distribution, the secondary skewness $\alpha_{2\phi}$ is most sensitive to the distribution within the tails of the sediment. Also, $\alpha_{2\phi}$ serves as a check on the continuity of the skew properties of a distribution, since it is numerically larger than α_ϕ for most simple distributions. In this connection, a skewness ratio, $R_\phi=\alpha_{2\phi}/\alpha_\phi$, is useful. A value of R_ϕ of approximately 2.7 is common, over a fairly wide range of skewness, if the curve can be approximated by either a Pearson Type III distribution or two terms of a Gram-Charlier series (see appendix). The use of R_ϕ in determining the type of distribution and the limitations to this system of graphic approximation to moment measures is discussed

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[9] Statistics texts (for example, Walker, 1947, p. 158; Mills, 1938, p. 158, and Yule & Kendall, 1948, p. 162) give an approximate formula for skewness,

$$\alpha_3=\frac{6(\text{Mean}-\text{Median})}{\text{Standard Deviation}}.$$

in the appendix and illustrated in figure 9.

The inclusion of the second skewness, together with the other measures, allows five significant points (ϕ_5, ϕ_{16}, ϕ_{50}, ϕ_{84} and ϕ_{95}) of the cumulative curve of a sediment distribution to be obtained from the listed data without resort to the original mechanical analysis of the distribution. Thus, if the five parameters are listed for a grain-size distribution, five significant points on the cumulative curve of the distribution may easily be computed (see table 1). This would increase the value of the data listed for a sediment in a report, and in many cases would eliminate the necessity of including the complete mechanical analysis of the sediment.

Measure of Kurtosis—Kurtosis is a measure of peakedness, and statistically is related to the fourth moment about the mean. There appears to be no simple graphic analogy for this moment. However, a measure sensitive to the peakedness of a distribution, the phi kurtosis measure, is defined as follows:

$$\beta_\phi = \frac{\frac{1}{2}(\phi_{16}-\phi_5)+\frac{1}{2}(\phi_{95}-\phi_{84})}{\sigma_\phi} = \frac{\frac{1}{2}(\phi_{95}-\phi_5)-\sigma_\phi}{\sigma_\phi}.$$

The phi kurtosis measure is a dimensionless measure of the average spread between the percentile diameters ϕ_5, ϕ_{16} and ϕ_{84}, ϕ_{95}, and is shown graphically in figure 4 as the quantity $\frac{1}{2}(a_1+a_5)$ divided by the standard deviation. This measure may be thought of as the ratio of the average spread in the tails of a distribution to the standard deviation of the distribution and thus is a measure of the degree of peakedness. For a normal distribution β_ϕ has a value of 0.65. If the distribution is less peaked than the normal, the tails have a greater spread as represented by the average distance between ϕ_5, ϕ_{16} and ϕ_{84}, ϕ_{95} and β_ϕ is greater than 0.65. Conversely, values of β_ϕ less than 0.65 indicate that the distribution is more peaked than normal.

Three of the sediment samples used for illustration in this paper are less peaked than normal, while the fourth, no. 60, has a β_ϕ value of 0.57, and is therefore more peaked than normal. The phi kurtosis measures for these samples are listed in table 3a, and the corresponding moment kurtosis β_2 are listed in table 5.

APPENDIX

The following discussion of moment measures and theoretical frequency distributions is given as an aid in understanding the relationship and limitations of the graphic parameters suggested in this paper to the analogous measures commonly used in statistics. The discussion of statistics is necessarily brief and limited in scope, and only those phases essential to the present study are considered. More detailed information regarding this subject may be obtained from textbooks on statistics (also see Krumbein & Pettijohn, 1938, Chapters 8 & 9).

Moment Measures—The term "moment" has its origin in mechanics, where the "moment of a force" is used to denote the product of a force and a distance from some origin, usually referred to as the fulcrum point. In statistics the frequency of the distribution replaces the "force" of mechanics, and the term statistical moment implies moment per unit frequency.

In mathematical statistics it is common practice to describe a frequency distribution in terms of moment measures. In general the first four moments provide an adequate description of a distribution, which when converted to the proper form are referred to as the mean, standard deviation, skewness, and kurtosis. In calculus notation, the "theoretical moment" of a distribution about the origin is defined as:

$$n_k = \frac{1}{N}\int_{-\infty}^{+\infty} x^k f(x)\,dx \tag{1}$$

where N is the total frequency, and $f(x)$ is the frequency function. The desired moment is obtained by setting k equal to 1, 2, 3, or 4. In practice, the equation for the frequency distribution $f(x)$ is usually not known. In this case it is customary to classify the data by dividing the distribution into equal class intervals in a manner similar to that used in constructing a histogram. The moment measures are then obtained by summing the individual moments for each class interval. A measure obtained in this manner will be referred to as the "data moment" about the origin, and is defined as:

$$n_k = \frac{1}{N} \sum_{i=1}^{h} x_i^k f_i \tag{2}$$

where x_i is the class mark (value of the mid-point of the class interval) of the ith class, f_i is the class frequency, and h is the number of classes.

Certain assumptions are made in the computation of data moments which in general make them less exact than theoretical moments. For example, it is assumed that the frequencies, f_i, can be considered as centered at the class marks, x_i. Thus if the data moments are to approach the value of the corresponding theoretical moments, it is necessary that the number of classes, h, be relatively numerous. Corrections for data moments are considered in most statistics texts, and will not be described here.

The first moment about the origin of the distribution, n_1, is the arithmetic mean and will be designated as M. It is customary to compute the remaining three moments about the mean of the distribution rather than the origin. Data moments about the mean are defined as:

$$m_k = \frac{1}{N} \sum_{i=1}^{h} (x_i - M)^k f_i. \tag{3}$$

Because the computation of data moments from their definitions (equations 2 & 3) is very tedious, it is convenient to use a short method based on a new variable, u, which takes on only small integral values. This variable is defined as $u = (x_i - x_0)/c$, where x_0 is a class mark chosen near the mean of the distribution, and c is the class interval. The class mark x_0, where u equals zero, becomes the origin when computing moments by the short mehod, and the various moments as defined by equation 2 then become moments about x_0 and will be denoted by v_k. These measures are converted to the appropriate moments about the origin and mean of the distribution by the following equations:

$$n_1 = M = cv_1 + x_0 \tag{4}$$

$$m_2 = c^2(v_2 - v_1^2) \tag{5}$$

$$m_3 = c^3(v_3 - 3v_1v_2 + 2v_1^3) \tag{6}$$

$$m_4 = c^4(v_4 - 4v_1v_3 + 6v_1^2v_2 - 3v_1^4) \tag{7}$$

The computations of the first four moments of sample 12 are shown in table 4. The class interval, c, used in this computation is ½ phi, and the total number of classes, h, is 10. The first column gives the class limits in phi units, the second column lists the midpoint or class mark, x_i, for each class, and the frequency for each class, f, in per cent is listed in column 3. The variable u is shown in column 4, with the zero value chosen in the class range 1.5 to 2 phi. Thus, the arbitrary origin, x_0, for the short computation is the midpoint of this class, and is equal to 1.75 phi.

The product of columns 3 and 4 gives the first moment for each class. The algebraic sum of these products (column 5), divided by the total percentage (100) gives, v_1, the first moment about x_0 as origin. The arithmetic mean, M, which is the first moment about the phi origin is obtained from equation 4. This equation gives a value of 2.11 phi units for M.

The second, third, and fourth moments about x_0 are given at the ends of columns 7, 9, and 11 respectively. Conversion of these measures to moments about the mean by equations 5, 6 and 7 give the following values:

$$m_2 = +0.354$$

$$m_3 = -0.277$$

$$m_4 = +0.827.$$

The standard deviation is defined as $\sigma = \sqrt{m_2}$ and is 0.59 phi unit for this distribution. The skewness measure α_3

is defined as m_3/σ^3 and is equal to -1.35. For a symmetrical distribution the skewness is zero; the negative sign of the skewness of sample 12 indicates that the median is greater (in phi units) than the mean diameter.

The moment measure of kurtosis is defined as $\beta_2 = m_4/\sigma^4$. For a normal distribution β_2 equals 3; if the distribution is more peaked than the normal β_2 is less than 3 and if the distribution is less peaked β_2 is greater than 3. The computations shown in table 4 give a value of 6.6 for β_2, indicating that the distribution is less peaked than a normal distribution.

The data moment measures for sample 12 were also computed using a class interval of $\frac{1}{4}$ phi, and 22 classes. The values of M, σ, α_3, and β_2 by this computation (not shown) were 2.11, 0.58, -1.46, and 5.8 respectively. These values are probably more nearly equal to the theoretical moment measures because the class interval is smaller and the number of classes are greater. The data moment measures, using a class interval of $\frac{1}{2}$ phi, for the four samples illustrated in this paper are listed in table 5.

Theoretical Distributions—Because data moments of distributions are more variable than theoretical measures, it is advisable to compare the approximate graphic measures recommended in this paper with theoretical moment measures of known distributions. Four common distributions which frequently apply to sediments are used for purposes of comparison; two of these, the Gram-Charlier series and the Pearson Type III are described below. The former is particularly useful for comparison because it is basically a normal distribution with skewness and kurtosis terms which are additive. Under certain conditions (Smith and Duncan, 1945, p. 84) the frequency distribution function for a Gram-Charlier series may be written:

$$f(x) = \frac{100}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}t^2} \left[1 - \frac{\alpha_3}{2}\left(t - \tfrac{1}{3}t^3\right) + \frac{\beta_2 - 3}{8}\left(1 - 2t^2 + \tfrac{1}{3}t^4\right) \right] \tag{8}$$

where $t = (x - M)/\sigma$ is a variable called a standard unit, e is the base of natural logarithms, and M, σ, α_3, and β_2 are respectively the theoretical mean, standard deviation, skewness, and kurtosis which were defined previously.

The cumulative frequency $F(x)$ between M and x, or between $t=0$ and $t=(x-M)/\sigma$, is obtained by integrating $f(x)dx$, and may be written:[10]

$$\begin{aligned} F(x) = {} & \frac{100}{\sqrt{2\pi}} \int_0^t e^{-\frac{1}{2}t^2} dt \\ & - \frac{50\alpha_3}{3\sqrt{2\pi}} \left[1 - e^{-\frac{1}{2}t^2}(1 - t^2) \right] \\ & + \frac{25}{6\sqrt{2\pi}} (\beta_2 - 3) \left[e^{-\frac{1}{2}t^2}(3t - t^3) \right] \end{aligned} \tag{9}$$

where $dx = \sigma dt$. The first term is the integral of the normal distribution, while the second and third terms, which are additive, express the skewness and kurtosis of the distribution. In a normal distribution $\alpha_3 = 0$, $\beta_2 = 3$, and the second and third terms vanish. The value of each of these terms for any value of t may be obtained from standard tables of the normal curve and its derivatives.

The Pearson Type III distribution, sometimes referred to as the incomplete Gamma function, is described in detail by Pearson (1922, p. v–xxxi) in the introduction to the tables of this function. The frequency distribution function may be written as:

$$f(x) = Ae^{-w}w^p \tag{10}$$

and the cumulative per cent function as:

$$F(x) = A \int_0^w e^{-w}w^p dw \tag{11}$$

where A is a constant chosen so that $F(x)$ equals 100 per cent when w approaches infinity, $w = px/a$, and a and p are constants related to the moment measures as follows:

$$M = \frac{p+1}{p} a \tag{12a}$$

$$\sigma = \frac{\sqrt{p+1}}{p} a = 1 \tag{12b}$$

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[10] The first two terms of equation (9) are developed in Otto, 1939, page 74.

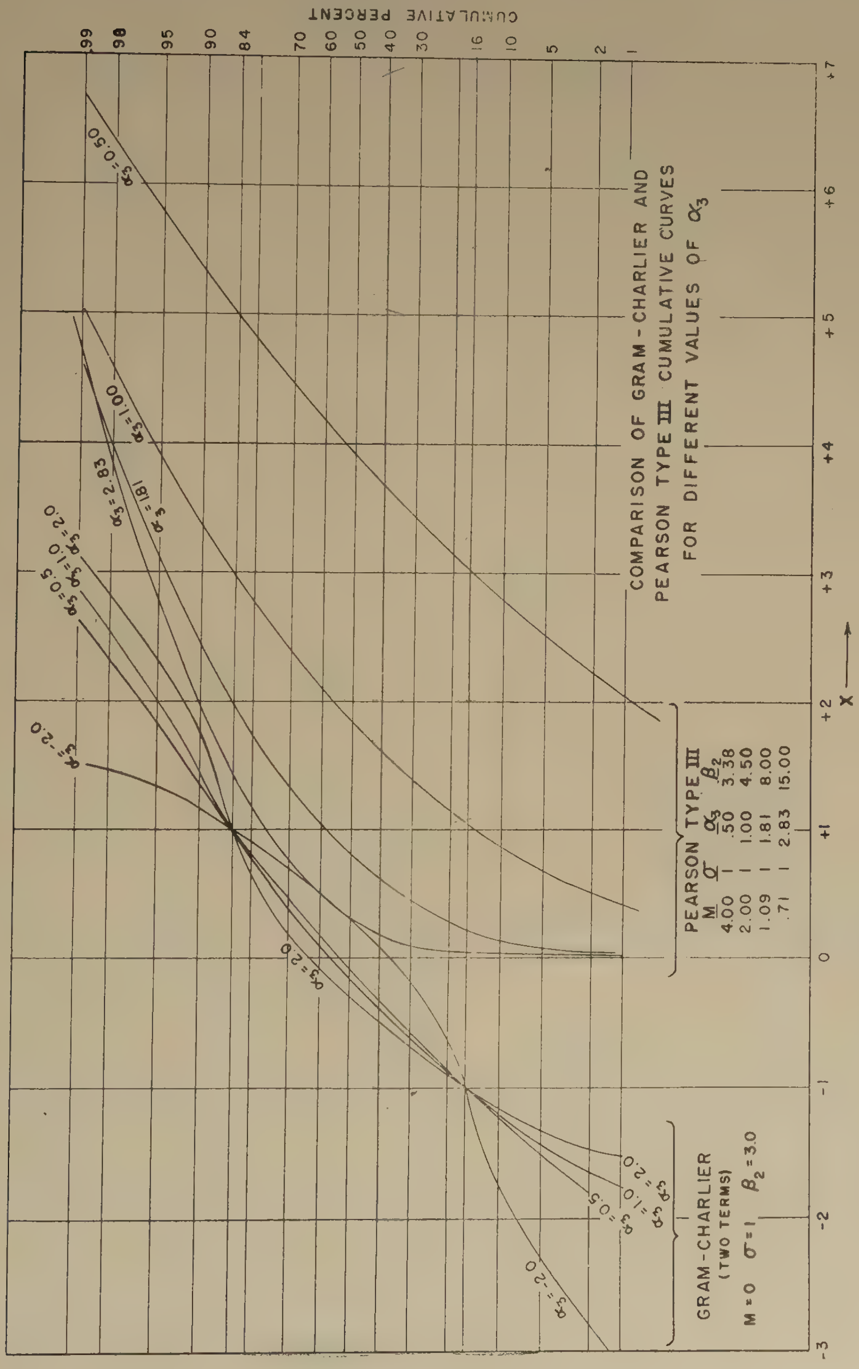
CUMULATIVE PERCENT
99
98
95
90
84
70
60
50
40
30
16
10
5
2
1
COMPARISON OF GRAM-CHARLIER AND PEARSON TYPE III CUMULATIVE CURVES FOR DIFFERENT VALUES OF α_3
PEARSON TYPE III
M σ α_3 β_2
4.00 1 .50 3.38
2.00 1 1.00 4.50
1.09 1 1.81 8.00
.71 1 2.83 15.00
GRAM-CHARLIER (TWO TERMS)
M = 0 σ = 1 β_2 = 3.0
α_3 = 0.50
α_3 = 1.00
α_3 = 2.83
α_3 = 1.81
α_3 = 2.0
α_3 = 1.0
α_3 = 0.5
α_3 = -2.0
α_3 = 2.0
α_3 = 2.0
α_3 = 1.0
α_3 = 0.5
α_3 = -2.0
-3
-2
-1
0
+1
+2
+3
+4
+5
+6
+7
X

Fig. 7.

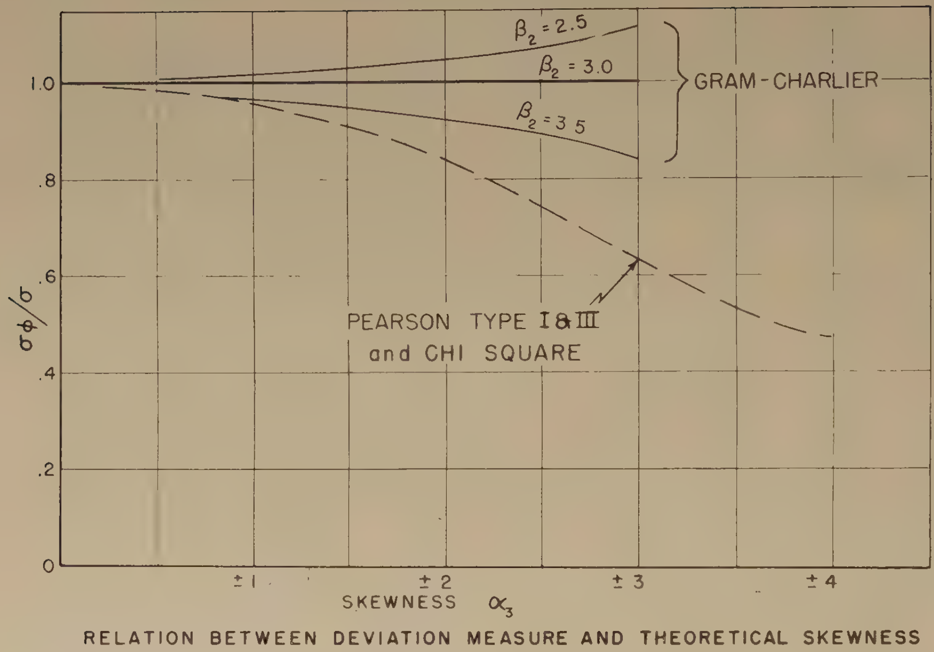

FIG. 8.—Ratio of the phi deviation measure, σ_ϕ, to the theoretical standard deviation, σ, as a function of the theoretical skewness, σ_3.

(12c) $$\alpha_3 = \frac{2}{\sqrt{p+1}}$$

(12d) $$\beta_2 = 3 + \frac{6}{p+1}.$$

For a distribution to be of the Pearson Type III it is necessary and sufficient that

$$2\beta_2 - 3\alpha_3^2 - 6 = 0.$$

This type distribution is skewed, and its frequency distribution curve as described by equation 10 has one finite end at $x=0$, while the other tail approaches zero as a limit as x becomes infinite. In the Pearson notation above, the x origin is at the finite end of the curve and the distribution has a standard deviation of one x unit. This notation may be used with some other variable, y, by the following transformation,

(13) $$x = \frac{y - M_y}{\sigma_y} + \sqrt{p+1}$$

where M_y and σ_y are the mean and standard deviation in the units of the y variable, and p is determined from α_3 in equation 12c.

Examples of Gram-Charlier and Pearson Type III cumulative frequency curves are shown in figure 7. Numerous cumulative curves representing both of these types were drawn by entering selected values of the theoretical moment measures in equations 9 and 11. In addition to the Pearson Type III and the Gram-Charlier distributions described above, numerous curves representing Pearson Type I[11] and Chi square[12] distributions were also drawn. The graphic measures M_ϕ, σ_ϕ, α_ϕ, $\alpha_{2\phi}$ and β_ϕ were computed for each curve, and compared with the corresponding theoretical measure M, σ, α_3 and β_2. The results of these comparisons are given in figures 8 and 9.

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[11] The Pearson Type I distribution is sometimes referred to as the incomplete Beta-function (Pearson, 1934).

[12] See Fisher & Yates, 1948, and Kenney & Keeping, 1951, p. 98.

Figure 8 shows the relation of σ_ϕ to the theoretical standard deviation, σ, for Gram-Charlier, Pearson Type I and III and Chi square distributions as a function of the theoretical skewness α_3. For skewness values near zero, σ_ϕ serves as a good approximation to the theoretical standard deviation. For higher degrees of skewness, σ_ϕ deviates appreciably from σ for the Pearson and Chi square type distributions, but serves as a fair approximation to the theoretical standard deviation for Gram-Charlier distributions if β_2 falls between 2.5 and 3.5.

Figure 9 shows the relation of the theoretical skewness α_3 to the phi skewness measure α_ϕ, the phi kurtosis measure β_ϕ, and the ratio of the two phi skewness measures, R_ϕ. The shaded areas in this figure represent confidence limits, such that a distribution whose β_ϕ and R_ϕ fall within their respective shaded areas, will have a theoretical skewness α_3 within the range of the shaded area opposite the phi skewness measure α_ϕ. This figure indicates that a good approximation to the theoretical skewness can be obtained for values of α_ϕ between -0.2 and $+0.2$.

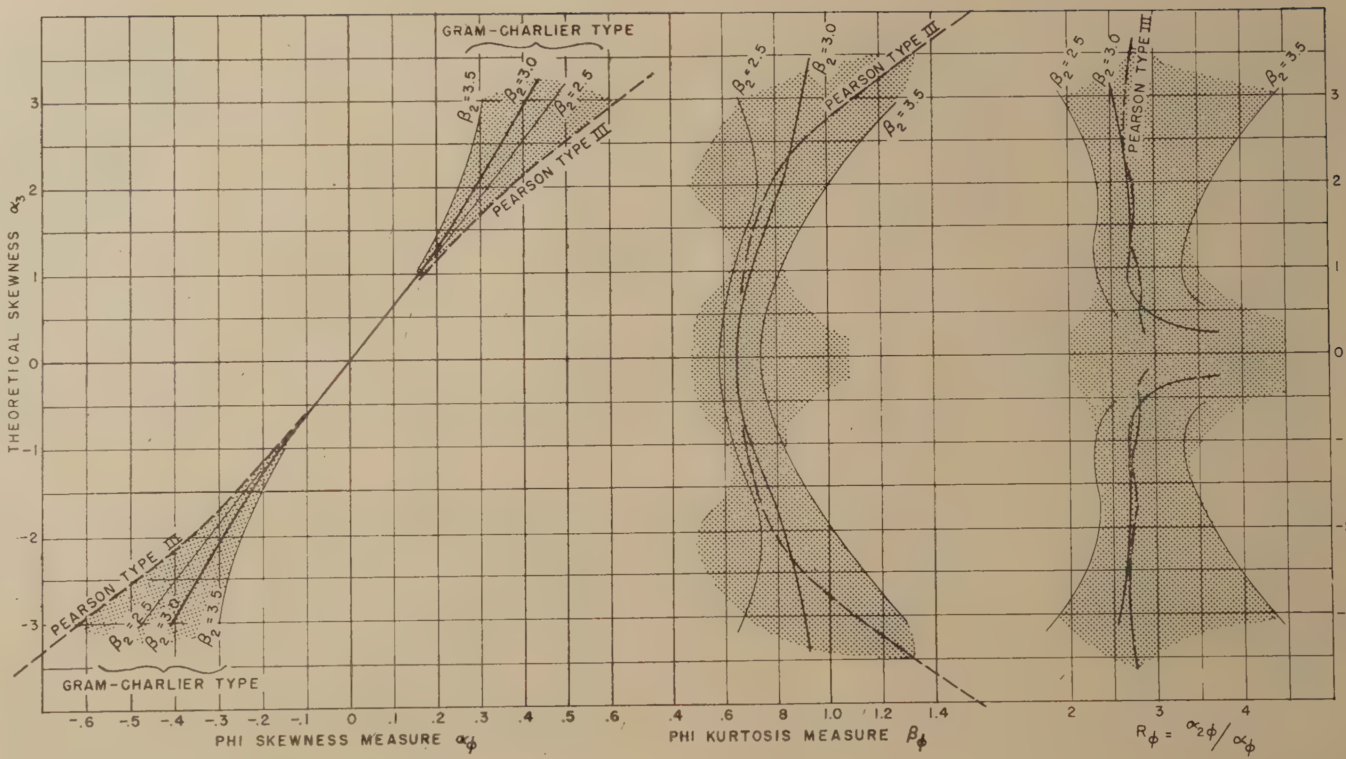
The approximation of the graphic measures to the corresponding theoretical moment measures decreases as the skewness of the distribution increases. Samples 3, 12 and 34 were chosen for illustration because they represent distributions with relatively high degrees of skewness for which it is difficult to deduce the theoretical measures from the graphic measures. For example consider samples 3 and 12. The phi graphic measures listed in table 3a suggest that, with the exception of the sign of the skewness, the distributions are quite similar. Plotting the phi skewness measure values of $+0.28$ and -0.29 in figure 9 together with the respective values of β_ϕ and R_ϕ shows that the distributions agree quite well with either the Pearson, the Chi square, or the Gram-Charlier type with $\beta_2=3.0$. This indicates that the theoretical skewness for either sample could fall between values of 1.6 and 2.0. If it is assumed that the distributions are either of the Pearson Type III, or Gram-Charlier ($\beta_2=3.0$), and that their α_3 values are between 1.6 and 2.0, then from figure 8 it can be shown that the ratio of σ_ϕ/σ must fall between 0.84 and 1.00. Since the samples have σ_ϕ values of approximately 0.5 phi, their theoretical standard deviations will fall between 0.5 and 0.6 phi.

Curve fitting techniques (described in most statistics texts) aided by the data moment measures for the samples shows that the distribution of sample 3 can best be described by a Gram-Charlier series with $\sigma=0.50$ phi, $\alpha_3=+2.0$, and $\beta_2=3.0$, while sample 12 is best described by a Pearson Type III distribution with $\sigma=0.56$ phi, $\alpha_3=1.60$ and $\beta_2=6.6$. The general form of the theoretical distributions for these two curves are given approximately in figure 7, by the Gram-Charlier curve having $\alpha_3=2.0$ and the Pearson Type III with $\alpha_3=1.81$.

The above analysis indicates that for distributions similar to 3 and 12, the theoretical mean, standard deviation, and skewness can be ascertained from the graphic phi measures, with about the same accuracy as is obtained from rough data moments. However, the phi kurtosis measure of distributions with this high degree of skewness cannot be used as an index of theoretical moment kurtosis. The phi kurtosis measure is only satisfactory in this regard for lower skewness values, altho it is a useful measure of the average spread in the tails of a distribution for all degrees of skewness.

CONCLUSIONS

Adoption of the graphic measures listed in table 1 would lead to a standardization of the descriptive measures for the grain-size distribution of sediments that is based on more rigorous statistical concepts than are most measures now in use. These measures have the advantage of being approximate graphic equivalents to the moment measures commonly em-



RELATION BETWEEN THEORETICAL SKEWNESS AND GRAPHIC PHI MEASURES

FIG. 9.—Relation between the theoretical skewness, α_3, and the graphic phi measures. Shaded areas represent confidence limits, such that a distribution whose R_ϕ and β_ϕ fall within their respective shaded areas will have a theoretical skewness value within the range of the shaded area opposite the phi skewness measure. The relation between theoretical skewness and α_ϕ, β_ϕ and R_ϕ for the Pearson Type III also applies approximately for Pearson Type I and Chi-square distributions.

CORRIGENDA FOR: Inman, D. L. "Measures for describing
the size distribution of sediments", Journal of Sedi-
mentary Petrology, Vol. 22, No. 3, 1952, pp. 125-145.

The sense in which "more" and "less peaked" are used under the section on Measure of Kurtosis on page 138 is contrary to common usage, as pointed out in a letter by Robert L. Folk of the University of Texas. The use of "peakedness" in this regard is unfortunate because as Kaplansky (Jour. Amer. Statistical Assoc., Vol. 40, 1945, p. 259) shows, "any combination of peakedness at the mean and kurtosis may occur". By kurtosis he means numerical value of the moment measure β_2. Kenney and Keeping (Math. of Statistic. Van Nostrand, 1951, p. 53) further state that a distribution with a perfectly flat top may have infinite kurtosis, and one with infinite peakedness may have values of β_2 less than 3. Similar objections also apply when describing kurtosis by such terms as platykurtic, mesokurtic and leptokurtic.

However, the following relations between the moment measure β_2; the phi kurtosis measure β_ϕ, and the "shape-description" of the frequency distribution curve are commonly found for many curves encountered in in practice:

β_2	β_ϕ	Description
3	0.65	Mesokurtic or normal (normal distribution curve)
$\beta_2 > 3$	$\beta_\phi > 0.65$	Leptokurtic or peaked (less flat-topped and longer tails than the normal)

$\beta_2 < 3$ $\beta_\phi < 0.65$ Platykurtic or less peaked
(curve relatively broad-shouldered with
depleted tails)

Perhaps the best definition of the phi kurtosis measure, β_ϕ, is that given on page 138, "this measure may be thought of as the ratio of the average spread in the tails of a distribution to the standard deviation (phi deviation measure) of the distribution..." If the tails of a distribution, that is the average value of $\phi_{95}-\phi_{84}$ and $\phi_{16}-\phi_5$, are longer than in the case of a normal curve with the same phi deviation measure, β_ϕ is greater than 0.65, and if the tails are shorter than normal β_ϕ is less than 0.65

Errors in printing are listed below:

Page 130, column 1, line 7, should read:
"frequency curve, are used in this study as"
Page 133, Table 3a, last line should read:
Phi Quartile Kurtosis^1, Kqϕ = ...
Page 135, Table 4, Moment about x_o for column (3)
$v_1 = +0.718$

Page 132, Table 2, fifth box should read: $\alpha_\phi = +0.28$

ployed in mathematical statistics, but are quickly and easily computed from five percentile diameters obtained from the cumulative frequency curve of the sediment.

The analogy between these measures and the moment measures of statistics should prove to be useful in many types of sediment studies. For example, it seems more meaningful to use measures of this type when investigating the relation between the grain-size distribution of transported material and the statistical distributions of properties in the transporting media.

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Some Fluorescent Substances Contained in the Marine "Blood Worm" (*Thoracophelia mucronata*)

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INTRODUCTION

Nutrition and biochromes of the bright red, hemoglobin-containing marine polychaete worm, *Thoracophelia mucronata*, have been studied recently by Fox, Crane, and McConnaughey (1). The animals, measuring 30–50 mm. in length when adult, live buried in the intertidal sand which they ingest in great quantities. Upon extraction of the worms with lipoid solvents, followed by chromatographic analysis, carotenoid pigments and several intensely bluish fluorescent zones were obtained. The latter exhibited chiefly single extinction maxima in light petroleum at 310, 306, 305, 302.5, and 300 mμ, respectively.[4]

Since, in the above study, spectral characteristics of the fluorescent substances from one particular lot of the worms (termed "sample 5") were recorded (here referred to as sample "I"), we have explored to what degree the fluorescent materials of the animals may be subject to variations. For this purpose two further, independently collected samples ("II" and "III"), each weighing 10–11 kg., were studied.

EXPERIMENTAL

The collection of marine blood worms is best accomplished in the following way: Since they are small, buried in the damp beach sand for depths of from 2 to 12 in.

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[1] Contribution No. 1712.

[2] This work was carried out on Contract NR-059-207 of the U. S. Office of Naval Research.

[3] Contributions from the Scripps Institution of Oceanography, University of California, New Series No. 582.

[4] The shorter wavelength regions were not explored because of lack of ultraviolet equipment at the time.

(depending upon physical conditions), and are required in great numbers, the sand in which they are living is shoveled into a screening device. For this purpose, we have found it useful to employ a plastic screen, 18 meshes/in., backed by a coarse galvanized wire screen or so-called "hardware cloth", to provide adequate support. These screens are in turn fastened to a cedar frame 36 in. long, 16 in. wide and 4 in. deep, which is supported above the sand at a height of from 1 to 3 ft. The mass of material on the screen is washed copiously with sea water to remove the sand which passes readily through the meshes. Contaminating organisms such as the sand crab *Emerita analoga*, the sand flea *Orchestia traskiana*, and bits of marine plant detritus, are removed by hand either directly from the screen or after placing the collected worms into a bucket and rapidly swirling the contents in fresh sea water, which brings the contaminants to the top of the mass. For further refinement in segregating the animals, in the event that but limited numbers are required, we leave the mass of worms on a dampened cloth or paper, shielding half of the assembly from light. In from several hours to an overnight period, most of the active, healthy members of the collection will have crawled out onto the darkened damp surface, thus cleaning their exteriors of adhering sand, and incidentally voiding much additional sand from the gut.

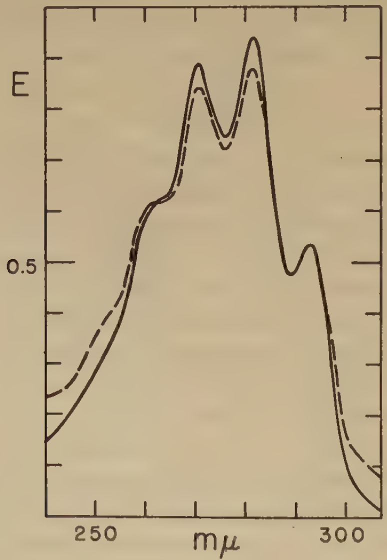

FIG. 1. Extinction curves in hexane: ——, crystalline steroid isolated from *Thoracophelia mucronata;* – – –, ergosterol.

The average dry weight of the total organic matter in the worms was determined to be 17.7%, the true ash 2.0%, and the sand contained in the gut 5.6%. Considering the manner of preparation of the material for shipment (rinsing most of the sand away with water but leaving some adhering to the mucus) and assuming that the gut is filled with sand, the total amount of the sand in the samples used was estimated to be about 10–12%.

Eleven kg. of the worms (sample II) was kept under acetone during transportation. After decantation, the material was ground in Waring blendors with fresh acetone to a fine slurry which was spun in a basket centrifuge lined with filter paper. The residue was extracted three times with hexane–acetone mixtures (1:1, 2:1, and 3:1). To the combined extracts benzene and excess water were added cautiously, and the lower phase was discarded. The upper one was combined with a benzene–hexane (1:1) extract of the acetone used originally to cover the worms plus that used in the blendors as mentioned. The total extract was concentrated *in vacuo* to 1 l. and the dark-brown, strongly bluish-grey fluorescing liquid was saponified by exposure to 0.5 l. of 20% KOH in methanol for ½ day. After the addition of water the benzene–hexane solution layer was washed alkali-free, dried

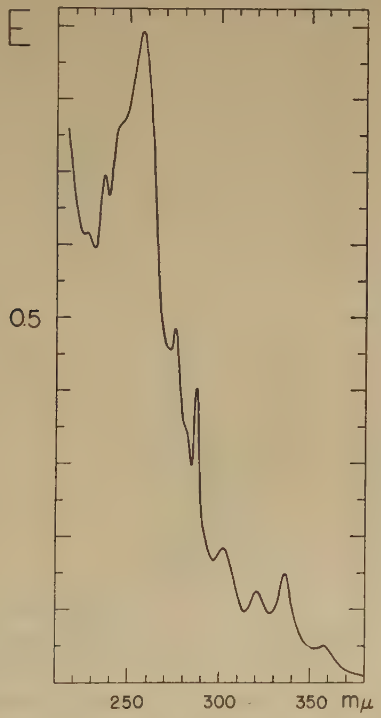

FIG. 2. Extinction curve in hexane of fluorescent fraction "*M*" *ex Thoracophelia* (sample II); the maxima located at the following wavelengths coincide with those typical for fluoranthene: 236, 275, 287, 302, 321, 336, and 358 mμ.

with sodium sulfate, and filtered with suction through a layer of Celite in order to eliminate particulate contaminants. This purification was completed by addition of excess acetone; the resulting precipitate formed was removed, washed with acetone, and discarded. The solution was then washed acetone-free and again dried. Concentration *in vacuo* yielded 100 ml. of a dark-red, intensely blue-fluorescent concentrate which was developed on a 30 times 8 cm. alumina–calcium hydroxide–Celite column (3:1:1) with a 1:3 benzene–hexane mixture. A sugar layer was stamped on atop the column to retard the downward migration of any gummy contaminants and thus prevent a possible split of the main column.

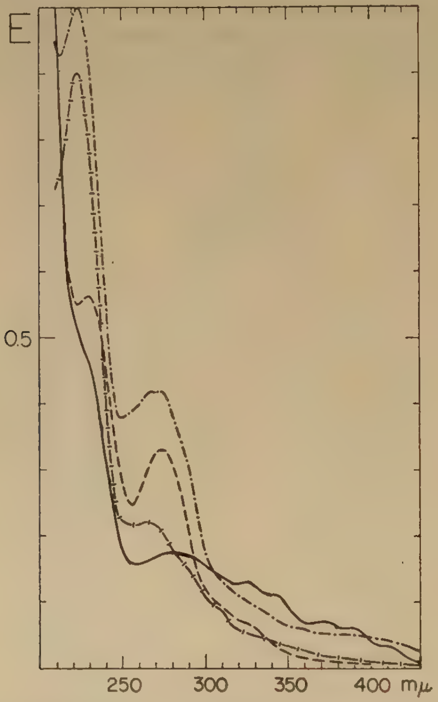

FIG. 3. Extinction curves in hexane of fluorescent fractions *ex Thoracophelia* (sample II): ——, fraction *A;* – – –, *B;* –·–·–·, *C;* –'–'–', *D.*

In Figs. 2–5 the alphabetic order *A–O* designates decreasing adsorption affinities on alumina–calcium hydroxide–Celite 3:1:1 (developer, hexane containing 0–50% benzene).

In the following chromatogram the left figures designate the width of the respective zones, in millimeters:

10 colorless (sugar layer).

48 yellow, orange and red zones; light brown to violet fluorescence throughout this section.
7 yellowish-green fluorescence with a yellow–orange pigment streak.
55 orange; bluish fluorescence.
180 colorless, very weak fluorescence at bottom.
Second filtrate fraction: colorless; blue fluorescence.
First filtrate fraction: colorless; blue fluorescence.

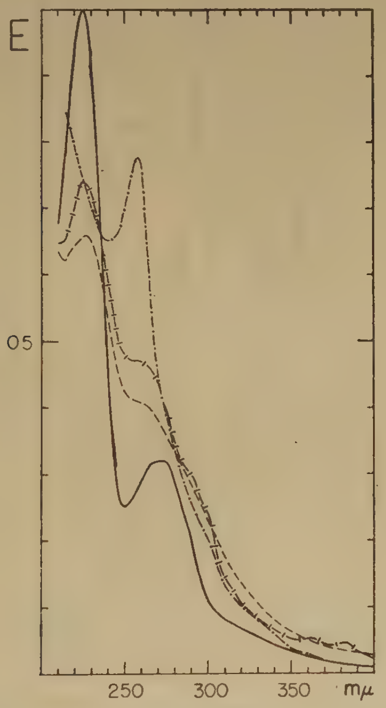

Fig. 4. Extinction curves in hexane of fluorescent fractions *ex Thoracophelia* (sample II): – – –, *E;* –'–'–', *F;* –·–·–·, *G;* ——, *H.*

Each of the adsorbed sections was cut out, eluted with acetone, transferred into hexane with water, washed, dried with sodium sulfate, and submitted to a systematic chromatographic fractionation in ultraviolet light. The details of these lengthy operations have been described by Petracek (3) as well as Koe(2) and will not be given here. Finally, about fifteen reasonably well separated zones were obtained (cf. legends to Figs. 2–5). Although a duplication of certain zones could not be absolutely excluded in a few instances, the individual nature of most of the components has been secured. Their adsorption affinities varied within broad limits: Some were rapidly washed through an alumina–lime–Celite column with such a weak developer as pure hexane, while others required the addition of 5–50% benzene to the hexane in order to be clearly developed and differentiated. In still other instances a strong developer such as pure benzene had to be applied.

The 48-mm. zone (see above) also yielded about 3 g. of a crystalline sterol as a by-product, the extinction curve of which appears in Fig. 1, compared with that of ergosterol.[5]

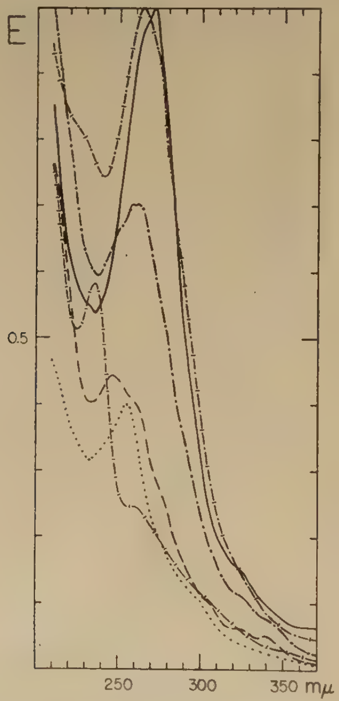

FIG. 5. Extinction curves in hexane of fluorescent fractions *ex Thoracophelia* (sample II): -'-·-', *I*; ——, *J*; -·-·-·, *K*; - - -, *L*; -'-'-', *N*; ······, *O*.

The worm sample III (10 kg.) was worked up in a similar manner, but using methanol in place of acetone [cf. (3)].

RESULTS

With reference to their chromatographically homogeneous, fluorescent constituents, the three blood worm samples investigated turned out to be quite different as shown in Figs. 2–5 (*ex* sample II) and in Fig. 6 (*ex* sample III). Moreover, none of these batches yielded the fluorescent compounds described earlier by Fox, Crane, and McConnaughey (1). Furthermore, samples II and III differed very widely from each other. The maximum extinction values for the numerous individual compounds were mostly observed in the region 220 to 280 mμ (in hexane).

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[5] Although the two curves in Fig. 1 are almost identical, and the composition of this substance was found to be $C_{27}H_{44}O$, the Carr-Price reaction product gave a spectral curve which was very different from those obtained from either ergosterol or a crude commercial sample of 7-dehydrocholesterol.

Figure 2 illustrates a special feature, viz. the occasional presence of aromatic polycyclic substances in the worms. The wavelength position of several (but not all) maxima of this fraction coincides with those typical for fluoranthene, a hydrocarbon which among others was recently identified in some barnacle extracts (4).

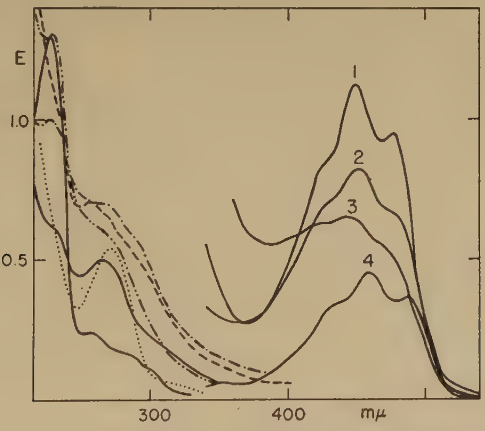

FIG. 6. Extinction curves in hexane of fluorescent fractions and of carotenoid pigments (1–4) *ex Thoracophelia* (sample III). (These fractions were separated chromatographically on calcium hydroxide–Celite 2:1 by developing with hexane containing 0–4% acetone.)

Evidently, in accordance with the great variety of organic materials adsorbed to the ingested sand, the marine blood worm is able to take up, and perhaps to store to a certain extent, fluorescent compounds of a wide chemical variety. In this connection there may be some significance to the demonstrated fact (1) that the worm not only fails to assimilate, but seems to degrade or otherwise alter the copious xanthophylls which greatly exceed the quantities of carotenes in its natural diet.

SUMMARY

Extracts of two large samples (10–11 kg.) of the marine annelid worm *Thoracophelia mucronata* were examined, by means of chromatographic

fractionation in ultraviolet light, for fluorescing substances. A great variety and variability of such compounds were found to be present in the worms, collected at different times from the same habitat.

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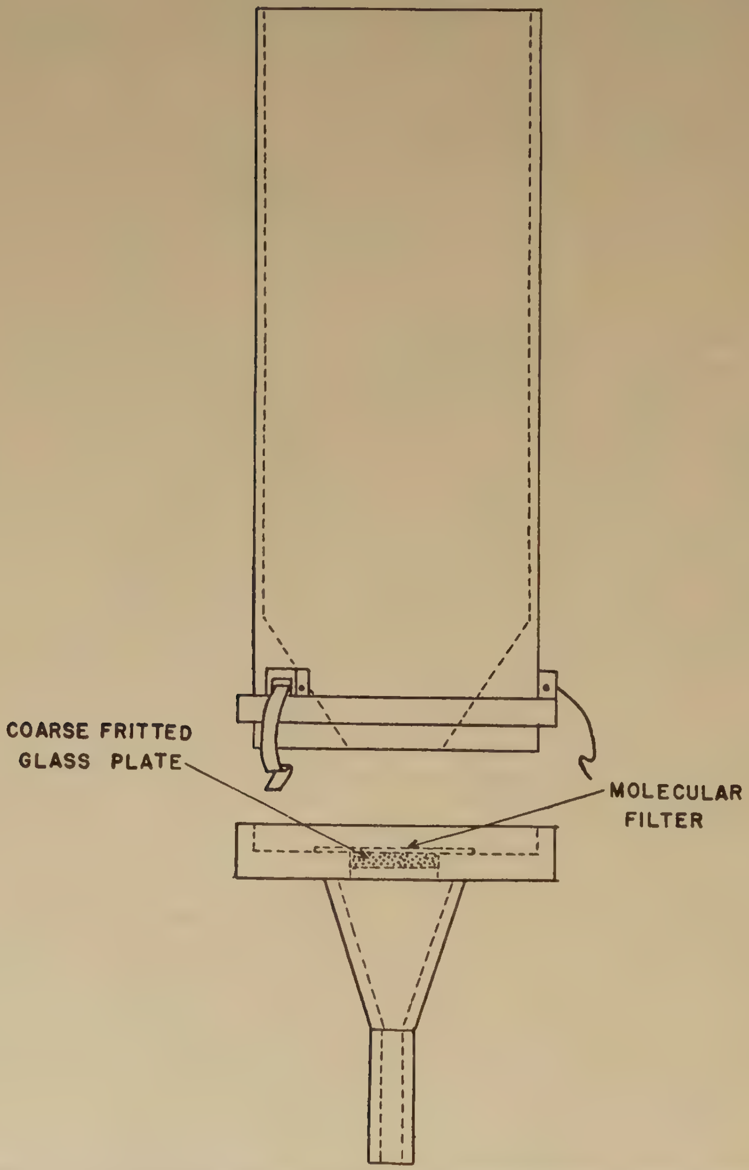
COARSE FRITTED GLASS PLATE
MOLECULAR FILTER

Figure 1. A filter apparatus constructed for use with the Molecular Filters. The unit may be fabricated from stainless steel or from plastics. The upper and lower unit are held together by means of distributor clips. The MF serves as a gasket to prevent water leakage from the apparatus.

difficulties. One or two liter samples of marine water, collected preferably in a hydrophobic plastic bottle, can be passed through the MF; thus all of the organisms with a maximum dimension larger than 0.5 μ, as well as many smaller bodies, are retained by adsorption on the upper surface. With subsequent fixing, staining, and preservation, this defined plankton population can readily be assayed both for type and volume of organisms. Many phytoplankton cells, when stained with Fast Green, suffer few if any morphological changes and may be readily recognized.

The technique can be readily used in field operations. About three hours are required to prepare a single sample, but this time can be reduced by simultaneous preparation of many collected samples if more than one filtering apparatus is available.

Sample Preparation.

1. To a freshly collected liter of sea water add 40 ml of a saturated solution of KI_3 to kill and fix the organisms.
2. After the fixed solution has stood for one hour pass it through an MF. Replace the excess iodine fixative and the sea water retained on the filter disc with distilled water by serial washes with graduated dilutions; draw ten ml of 5, 10, 25, 50, 75, 90 and 100% dilutions with distilled water through the MF under vacuum.
3. Add 20 ml of a Fast Green dye solution (Johansen, 1940: 59) and leave in contact with the membrane for 30 minutes.
4. Draw the dye solution through the filter apparatus and pass distilled water through the membrane until the unadsorbed dye is thoroughly removed.
5. Dehydrate the organisms with a graded series of solutions of ethanol in distilled water; pass each of the washes of the series—5, 10, 25, 50, 75, 90 and 100% alcohol by volume—through as rapidly as possible to minimize dissolution of the membrane by the alcohol. Optional use may be made of higher alcohols, such as propanol or butanol, which are somewhat less destructive.
6. Render the water-free membrane transparent with cedar oil by drawing through it serial dilutions of 10, 25, and 50% cedar oil in alcohol, and finally 100% cedar oil. When the pure cedar oil has been drawn through, remove the cleared membrane from the filter, halve, and mount in balsam on a microscope slide.
7. For preservation, a small crystal of thymol may be dissolved in 100 ml of the cedar oil or balsam.

In order to remove any contaminating particles, all reagents and rinsing fluids are initially passed through an MF. These solutions are kept in covered containers to protect them from recontamination by air-borne dust particles. Indigo-carmine picrate has been employed alternatively as the dye, although the organisms are not so strikingly stained with this as with Fast Green. Karo syrup can be substituted for the alcohol and cedar oil in the dehydration and clearing processes. Serial dilutions of the sugar solution in water passed through the MF, as in step 5 above, produces a cleared membrane suitable for mounting.

TABLE I. SIZE DISTRIBUTION OF PLANKTON AS MEASURED ON A MF

Size range of organisms (Average radius) μ	*Number of organisms*		*Volume* μ³	
	Sample A	*Sample B*	*Sample A*	*Sample B*
1	199	491	834	2,476
4	101	160	27,078	42,895
6	89	105	80,529	95,007
8	44	50	94,370	107,238
10	29	21	121,481	87,969
12	10	12	72,368	86,863
16	15	20	257,370	343,160
18	5	1	122,151	24,430
20	5	3	100,536	167,560
24	7	9	405,363	521,181
32	2	7	65,536	229,376
40	2	—	536,192	——
48	2	1	926,540	426,270
64	1	—	1,098,121	——
	TOTAL		3,908,469	2,171,425

Both surveys made on 28 March 1952. Samples 500 ml in volume. 50 microscopic fields studied out of 256 fields of filtered area.

Quantitative estimates can be made of the total volume of plankton contained upon an MF by ascertaining the total number of organisms and their respective average radii in a representative number of fields of the microscope. By assuming that the individual cells are approximate spheroids, the volume of the stained organic matter is determined. Where long chains of diatoms or plankton of known asymmetric shape are encountered, their volume may be calculated mathematically. Table I depicts a typical distribution of plankton with respect to size.

The static picture of the standing crop represents but a transitory condition in a dynamic process. The production of organic matter by a given standing crop has been investigated by the measurement of photosynthetic oxygen in a collected sample of sea water, or by the more recently developed method of the fixation of radioactive carbon dioxide (Nielsen, 1951). In waters where the planktonic populations are low or where but little growth is encountered, the oxygen method is not satisfactory, whereas the newer technique is much more sensitive to the photosynthetic fixation of very small amounts of carbon dioxide.

In the radioassay of productivity, add a one ml aliquot containing one microcurie of radioactive carbon[2] as dissolved $NaHC^{14}O_3$ to a freshly drawn liter sample of sea water. The total inorganic carbon content of the water is determined chemically and is directly proportional to the initial activity of the radioactive carbon, since the quantity of carbonate introduced with the active tracer is negligible in relation to the amounts of carbonate normally present in sea water. After photosynthesis by the resident organisms has proceeded for a determined time under conditions comparable to those of the marine environment, the entire sample is collected on an MF. The filter is washed with inactive sea water, dehydrated in a desiccator, and assayed radiometrically for the carbon taken up by the organisms (Table II).

TABLE II. Carbon Dioxide Fixation by Standing Crop of 28 March 1952

	Net counts/minute of filtered plankton	*Per cent of CO_2 of water removed by plankton/day*	*Micro-equivalents CO_2 of sea water removed by plankton/day*
Sample 1	304.5	0.85	16
Sample 2	323.5	0.90	17

One liter samples taken. 1.91 milli-equivalents CO_2/L of water of chlorinity = 18.32. Specific activity of C^{14} initially added = 36,000 counts/min/L.

The organisms are retained on the top of the membrane, not penetrating into the lower portion, and hence any absorption by the filter disc of the weak beta rays emitted by the fixed radioactive carbon is minimized. Further, the complete retention of all plankton above a size of 0.5 μ gives a measure of productivity usable in the quantitative equations of Riley, Stommel, and Bumpus (1949).

Estimation and Characterization of the Inorganic and Organic Suspended Matter. The suspended material of marine waters has been investigated with regard to the over-all inorganic chemical composition (Armstrong and Atkins, 1950) by routine chemical analyses of the sediment collected from an average of 22 liters of sea water. Jerlov (1951) has studied the distribution of suspended particles in the sea by the intensity of light scattered from a Tyndall beam. Fox, Isaacs and Corcoran (1952) have determined the organic carbon and organic nitrogen in marine leptopel by wet combustion of the material retained on inert inorganic powder. Krey (1949, cited by Jerlov), by fractional filtration, has subjected the collected particles to microscopic analysis; he also studied the chemical constitution of the suspended organic matter. However, none of these methods can give size distributions and chemical constitution on the same sample.

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[2] The radioactive C^{14} used in this investigation was supplied by the Oak Ridge National Laboratory on allocation from the Isotopes Division, U. S. Atomic Energy Commission.

The MF has been used to advantage in the study of the size distribution of particles containing suspended iron in coastal marine waters. Recent studies on the growth of marine diatoms have indicated that particulate or colloidal iron is utilized as a growth nutrient (Harvey, 1935; Goldberg, 1952) and may actually be a limiting factor in their multiplication. Thus, a semiquantitative technique has been developed to ascertain the number and size of particles containing iron in a water sample. It should be emphasized that the chemical combination of the iron has not actually been determined. In all probability it occurs chiefly as hydrous ferric oxides.

Sample Preparation.

1. One or two liters of sea water are passed through the MF. The collected residue and the MF are washed with distilled water to remove any salts which would otherwise inhibit the clearing of the membrane.

2. The MF is dehydrated in a desiccator or dried in an oven for 5 minutes at 100° C.

3. The membrane is placed on a microscopic slide and covered with a few drops of "Tween 80" (polyoxythylene sorbitan monooleate, available from Atlas Powder Company, Wilmington, Delaware) which has been saturated with potassium thiocyanate and acidulated with hydrochloric acid (3 drops concentrated HCl per 100 ml of "Tween 80").

The "Tween 80" has an index of refraction close enough to that of the MF to clear the filters and render visible the deep red zones of iron thiocyanate complex which form about the iron particles. A typical distribution of iron particles in water taken from the pier of the Scripps Institution of Oceanography is shown in Fig. 2. A filter apparatus constructed completely of plastic, similar in design to that shown in Fig. 1, is utilized in these analyses.

The dried weight at 110° C and the ash weight of the sediment collected upon an MF from a given volume of sea water and subsequently washed free of soluble salts with distilled water can be used to define semiquantitatively the amount of inorganic and organic fractions. The MF is ashless and has a weight of about 95 mg reproducible to ± 0.2 mg after repeated washings and dryings at 100° C.

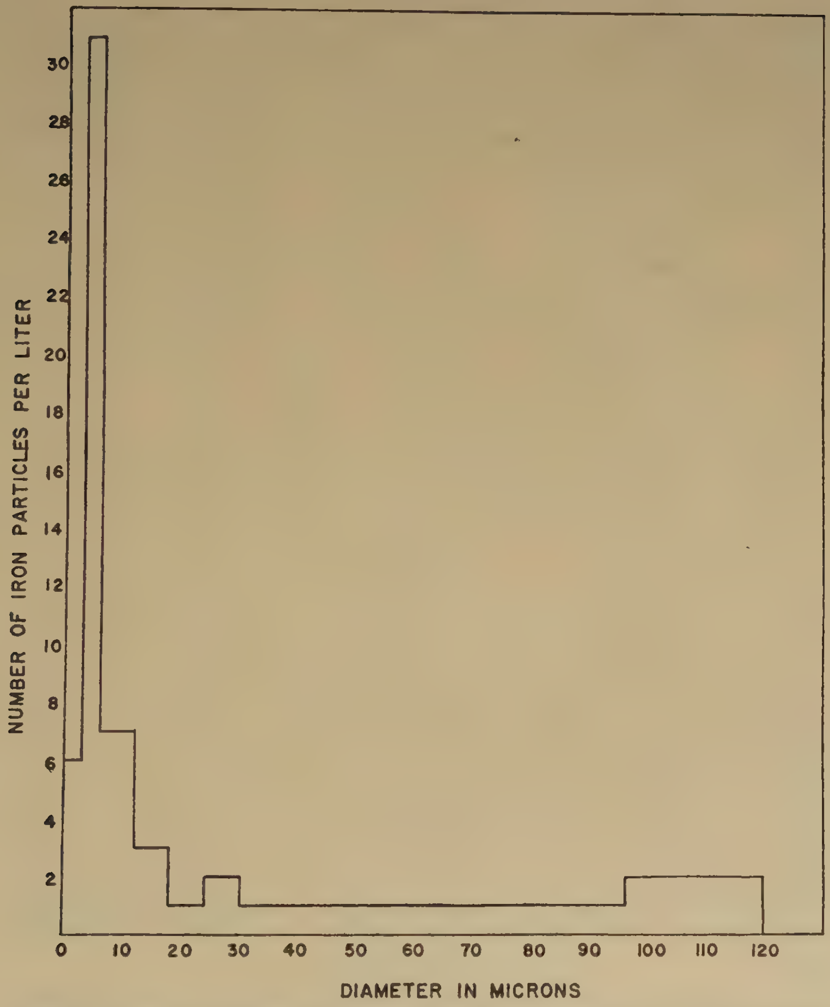

Figure 2. The size distribution of suspended particles, giving a positive thiocyanate test for iron in surface water collected six miles west of La Jolla, California.

Two inshore surface samples of one liter volume showed 1.9 and 6.2 mg of total dry weight and 1.3 and 4.4 mg of ash weight respectively. By difference the "organic content" would be 0.6 and 1.8 mg. A profile of suspended matter in the open ocean is given in Table III.

Discussion. The quantitative assay of both planktonic populations and suspended sediments has demonstrated that improvement in sampling techniques is necessary for precision in the results. This is manifest in the volumetric analysis of plankton in Table I, where one large organism of diameter 64 μ accounts for one fourth of the volume estimated for a 500 ml sample. Duplicate assays of the same water sample differed by a factor of two. In other size distribution studies of plankton, two similtaneously collected samples were often a whole order of magnitude apart. Comparison between pairs of samples subjected to the radiometric determination of carbon uptake show the same kind of deviation but to a less extent. The distribution of suspended sediment, as illustrated in Table III, exhibits considerable scatter.

TABLE III. THE DISTRIBUTION OF INORGANIC SUSPENDED MATTER

Depth *(m)*	*Ash Weight at 400° C* *(mg)*	
	Sample A	*Sample B*
0	1.2	2.7
10	2.1	7.7
25	1.2	1.3
50	1.3	0.4
75	0.0	0.2
100	1.6	0.2
150	6.0	1.0
200	1.0	7.3
300	2.4	0.5
400	0.8	3.8
500	1.0	0.7
600	—	0.8
800	4.7	1.6
1000	1.3	2.2
1200	1.6	0.5

Samples were 1.2 liters. Sample A collected 28 February 1952 at 1630. Sample B collected 29 February 1952 at 0700. Collections made in San Clemente Deep off San Diego, California.

These results emphasize the discontinuous arrays of suspended solid phases within natural waters. Thus, the amount of substance collected over a short time interval from a unique location will not necessarily represent conditions in the water region; rather, they may reflect the layering of the water masses or the turbulence of the area. To overcome these difficulties, two lines of approach, not mutually exclusive, are indicated. To secure more valid data for statistical representation of a given water mass would require the processing of voluminous samples from a considerable number of strata. Such a comprehensive survey would manifestly require much time and labor.

The collection of a sample integrated over time and space in a given locality is preferable where time is limited. A simple water sampler for volumes of one or two liters may be readily constructed by the use of a capillary bleeder. In the opening of the collection device two glass tubes may be held in place by a cork: one tube of large diameter for water inflow and a second tube of drawn capillary tubing for air release. By controlling the size of the capillary, filling times can be rigidly controlled.

Acknowledgment. The authors wish to acknowledge the generous donation of experimental molecular filters from Dr. Alexander Goetz of the California Institute of Technology during the initial stages of this investigation. James S. Kittridge aided in collection of the samples at sea.

Summary. 1. The standing crop of marine phytoplankton populations can be quantitatively estimated for all organisms larger than 0.5 μ by a filtering technique that utilizes the molecular filter, a cellulose acetate and nitrate membrane. The organisms are collected, fixed, dehydrated, stained, estimated as to size and number and preserved on one of these filter discs.

2. The molecular filter can be used in the quantitative assay of suspended organic and inorganic matter of natural waters.

3. The size distribution of suspended iron particles was studied by applying microchemical analyses to material collected on the molecular filter.

4. The suspended matter in marine waters was found to be inhomogeneously distributed. It is proposed that larger samples or integrating collecting devices be utilized to obtain the true picture of the dispersed suspensions.

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ABSORPTION OF NUTRIENTS BY AQUATIC PLANTS

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ABSTRACT

Formulae are derived for the rate of nutrient absorption by aquatic plants approximating the shapes of spheres, discs, cylinders, and plates. Other parameters are the size and specific gravity of the plant, the nutrient concentration of the medium, and the physical properties affecting the transfer of nutrients toward the plant surface. The formulae allow for convection, i. e., the movement of water relative to the plant. Hence absorption is aided by a current in the case of attached plants and by a rapid sinking rate in the case of plankton. The results are not materially modified by turbulence.

The formulae are applied to problems of diatom growth and adaptation. Any division rate of diatoms corresponds to a certain *minimum* rate of nutrient absorption; this in turn requires a certain sinking rate and therefore a certain excess in specific gravity of the diatoms over that of the surrounding water. In well fertilized laboratory media the excess may be very small, and this is consistent with the slow sinking rates usually observed under laboratory conditions. Under impoverished natural conditions the excess must be much larger, and hence there is a flotation problem. Accordingly, the analysis was extended to take into account sinking rates and vertical overturn in addition to nutrient absorption. The results are realistic with regard to observed division rates and sizes of diatoms, but they indicate an inherent competitive advantage of small diatoms over large ones. The observed size-frequency distribution of diatom species can be accounted for if one introduces an arbitrary predation factor which assumes that small cells are eaten more readily than large ones and that spheres are more acceptable food for small animals than long cylinders and plates.

1. INTRODUCTION

It is commonly stated in the literature that the elaboration of diatoms into flat discs, plates, and more intricate shapes is a flotation device. However, this hypothesis ignores the existence of equally common adaptations that have the opposite effect. For example, the formation of centric diatoms into chains reduces the total surface area

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[1] Contribution from the Scripps Institution of Oceanography, New Series No. 584. We are indebted to Marston C. Sargent for proposing the problem and examining the manuscript.

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and thereby increases the sinking rate. While the necessity of adequate flotation cannot be denied, we must look further for a logical explanation of the whole array of observed morphological variations.

The absorption of essential nutrients is an aspect of phytoplankton ecology that involves both surface-volume relations and sinking rates. Ecological evidence indicates that the rate of absorption often puts an upper limit on plant growth in the sea. This is most likely to occur in warm and stable waters that are also critical from the standpoint of flotation. If variations in size and shape in the diatoms have survival value, the problem should be analyzed in terms of both sinking rates and absorption.

The coexistence of a variety of forms and sizes of diatoms in nature implies that each variety has a slight advantage over the other in a particular set of circumstances, but no single variety maintains an advantage in all circumstances. It remains to be seen whether slight differences of this sort can be detected experimentally. In the present paper we shall take the obvious preliminary step of investigating the underlying physical principles by theoretical methods. Brief attention will also be given to the related problem of absorption by attached plants.

A small grain of solid material sinking through water will absorb heat by *diffusion* and by *forced convection.* We shall assume that the physical laws governing these two processes give also an adequate description of the processes whereby sinking diatoms absorb nutrients. This permits us to be quantitative, within limits.

Unfortunately the theory of forced convection has not been developed to a point where it can easily be applied to our problem. Our knowledge of this subject rests mostly on experimental evidence guided by dimensional analysis. The experiments have been performed largely on wires, spheres and plates for which the Reynolds numbers are larger by at least one order of magnitude than those applicable to sinking diatoms. In order to extrapolate the experimental results into the region of interest, it is necessary to have some guidance from theory as to what should be expected at very small Reynolds numbers. The associated mathematical problem is surprisingly difficult, and there are several published accounts describing these difficulties without giving solutions. The first adequate approximation[2] has been found only very recently by Kronig and Bruijsten (1951), and this work makes it possible to discuss with confidence the relationships for the scale with which we are concerned.

The derivation of these relationships are cumbersome and uninteresting and are contained in Appendix I, pp. 235–239.

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[2] See footnote 10 on p. 240.

2. THE ABSORPTION AND SINKING RATES

Consider a diatom of mass m, containing rm grams of phosphate. Thus r designates the fraction in body weight of phosphate. Suppose q grams of phosphate are transferred each second from the surrounding water to the diatom. The relative rate of absorption may then be expressed by

$$\tau^{-1} = \frac{q}{rm}, \tag{1}$$

where τ is a measure of the time required to absorb as many grams of phosphate as are initially contained. The time required for a diatom to split in two cannot be much shorter than τ, but it may be longer because of other limiting factors. We shall call τ the "absorption time."

Different nutrients lead to different absorption times. The nutrient with the largest absorption time imposes the most severe limitation on the possible rate of growth.

The problem is to obtain q. It depends on the dimensions of the plant and on the physical characteristics of the surrounding fluid. It will be much larger if the fluid moves past the plant (or vice versa) and continually renews the nutrients in an impoverished film immediately surrounding the plant than if there is no such relative motion. The effect of the moving water is designated as "forced convection," the remaining part as "diffusion."

The forced convection depends on the velocity v of the fluid relative to the plant. This velocity is measured at some distance, say at least three diameters, from the plant, where the disturbing effect on the flow by the plant itself is negligible. We must distinguish between attached[3] plants and freely sinking plants. In the former case the velocity v is an independent variable and is determined by wave action, currents, etc. In the latter case v is dependent only on the properties of the plant and the fluid, provided the effect of turbulence does not have to be taken into account. Apparently this is the case, as will be shown.

The solutions have been derived for five cases: an attached plate, a freely sinking plate, disc, sphere and cylinder. The geometry and dimensions are given in Fig. 1. Such simple geometric arrays are quite inadequate to represent intricate plant forms. All that can be said is that this is the best that can be done and that it is better than making no calculations at all. An indication of the uncertainties arising from the representation of plants by simple geometric bodies

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[3] The term "attached" has no bearing here on a flow of nutrients through the stem.

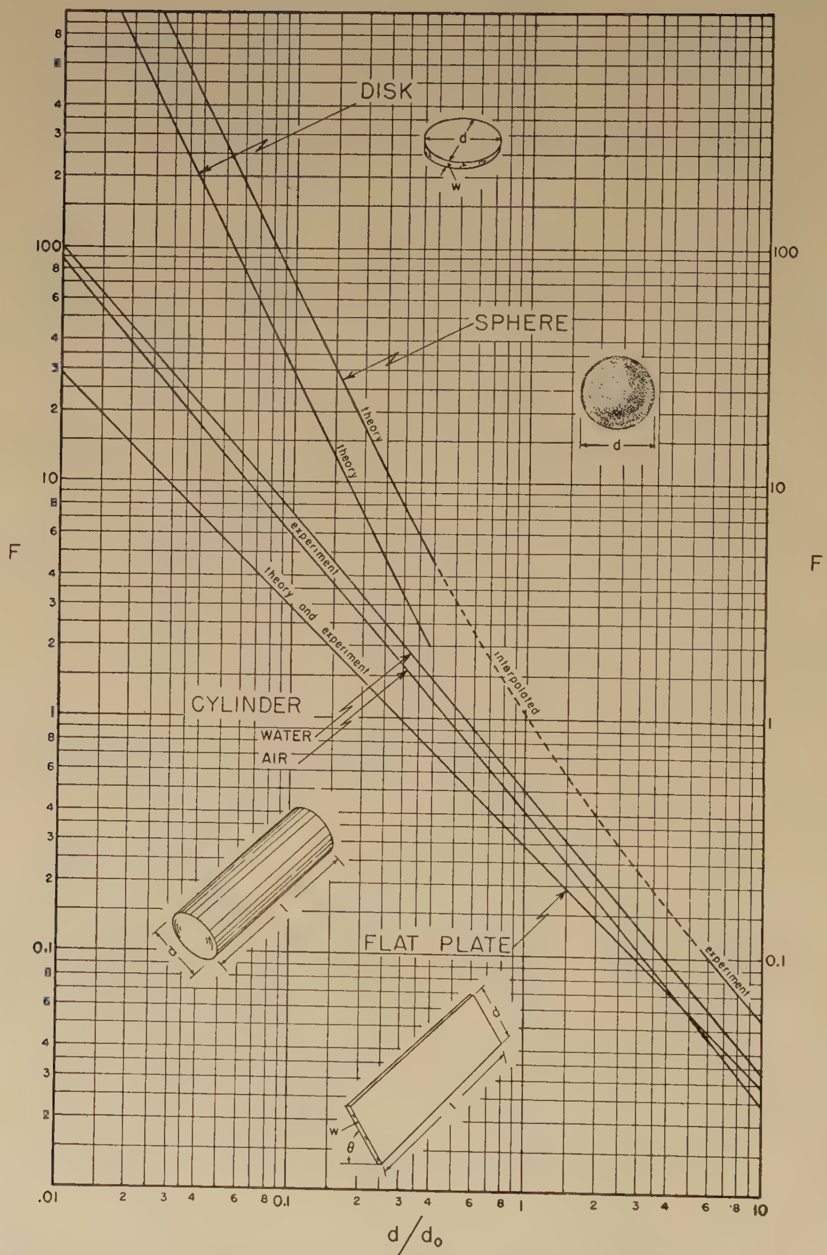

Figure 1. Plot of the relative absorption rate, F, as function of the diameter, d, for various geometric shapes: a flat plate sinking obliquely along a plane inclined by an angle θ, a sphere, disc and cylinder sinking vertically as shown. In the case of a sphere, the theoretical relation for $d/d_0 < 0.4$ can be smoothly joined to the empirical relation for $d/d_0 > 5$. In the case of the flat plate the theoretical relation has been confirmed by experiment. In the case of the cylinder the relation is wholly empirical. In the case of the disc, it is theoretical. The relations hold for water and air, except for cylinders, where separate curves have been constructed.

is found in the variability of the results among the geometric bodies themselves. The terms of the equations are defined as follows:

v	in cm $\sec^{-1}$	velocity of fluid relative to plant, at large distance from plant;
ϕ	in g cm^{-3}	excess in concentration of nutrient at large distances from plant over concentration at surface of plant;
m	in g	mass of plant;
r		mass of nutrient in plant divided by m;
ρ	in g cm^{-3}	density of surrounding fluid;
$\Delta\rho$	in g cm^{-3}	mean density of plant minus density of fluid.

The absorption rates in $\sec^{-1}$ are given by

attached plate:[4] $$\tau^{-1} = \frac{\phi}{r\rho}\,\frac{1}{wd^{\frac{1}{3}}}\,(k'v)^2\,; \tag{2}$$

sinking plate:[4] $$\tau^{-1} = \frac{\phi}{r\rho}\left(\frac{\Delta\rho}{\rho}\right)^{\frac{2}{3}}\tau_0^{-1}\left(\frac{d^2}{w^2}\sin\theta\right)^{\frac{1}{3}}F_p\,; \tag{3}$$

sinking disc: $$\tau^{-1} = \frac{\phi}{r\rho}\left(\frac{\Delta\rho}{\rho}\right)^{\frac{2}{3}}\tau_0^{-1}\,\frac{d}{w}\,F_d\,; \tag{4}$$

sinking sphere: $$\tau^{-1} = \frac{\phi}{r\rho}\left(\frac{\Delta\rho}{\rho}\right)^{\frac{2}{3}}\tau_0^{-1}\,F_s\,; \tag{5}$$

sinking cylinder: $$\tau^{-1} = \frac{\phi}{r\rho}\left(\frac{\Delta\rho}{\rho}\right)^{\frac{1}{3}}\tau_0^{-1}\,F_c\,. \tag{6}$$

The sinking rates[5] in cm $\sec^{-1}$ are

plate: $$v = v_0\left(\frac{w}{d}\sin\theta\right)^{\frac{2}{3}}Pr^{\frac{1}{3}}\,F_p'\,; \tag{3a}$$

disc: $$v = v_0\,\frac{w}{d}\,F_d'\,; \tag{4a}$$

sphere: $$v = v_0\,F_s'\,; \tag{5a}$$

cylinder: $$v = v_0\,F_c'\,. \tag{6a}$$

We shall also need

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[4] For the plate we have assumed diffusion negligible compared to forced convection, as will be the case except for extremely small values of v.

[5] The expressions for the sinking rate are more elaborate than ordinarily required in order to make it possible to plot the F and F' function against the same parameter d/d_0. Thus the diffusivity k enters through v_0, and hence v_0 on one hand, and through δ_0, and hence d_0 on the other hand, but actually the sinking rate is independent of k.

$$d_0 = \delta_0(\Delta\rho/\rho)^{-\frac{1}{3}}, \qquad v_0 = \upsilon_0(\Delta\rho/\rho)^{\frac{1}{3}}. \qquad (7)$$

Definitions and values are contained in Table I. Scale factors of time, τ_0, of diameter, δ_0, and of speed, υ_0, depend only on the viscosity and diffusivity of the surrounding medium. The effect of size is contained in the F and F' functions. These are plotted in Figs. 1 and 2 against d/d_0, where d is the diameter (the length in the direction of flow in the case of the plate). Numerical examples are given in Section 4. Table I and Figs. 1 and 2 deal with water and air, but no application will be made to conditions in air.

TABLE I. DEFINITIONS AND VALUES OF CONSTANTS

			Water	*Air*
ν	cm² sec⁻¹	viscosity at 20° C	0.01	0.15
k	cm² sec⁻¹	diffusivity* at 20° C	$2\text{x}10^{-5}$	0.15
k'	cm² sec⁻¹	$1.8\ k^{4/3}\ \nu^{-1/3}$	$4.5\text{x}10^{-6}$	0.27
Pr		Prandtl number, νk^{-1}	$5.0\text{x}10^{2}$	1.00
τ_0	sec	$(\nu^2/g^2k)^{1/3}$	$1.73\text{x}10^{-2}$	$0.54\text{x}10^{-2}$
δ_0	cm	$(72\nu\ k/g)^{1/3}$	$0.24\text{x}10^{-2}$	$12.0\text{x}10^{-2}$
υ_0	cm sec⁻¹	$(k^2\ g/72\nu)^{1/3}$	$8.17\text{x}10^{-3}$	1.27

* The diffusion coefficient may vary by a factor of two depending on the nature of the solute.

3. ATTACHED PLANTS

We shall represent a leaf by a thin plate of density ρ and with the dimensions given in Fig. 1. The flow is along d. The surface area on both sides is $s = 2ld$, and the mass $m = \rho l d w = \rho(\frac{1}{2}\,s)w$. It follows from equation (1) that

$$\frac{q}{s} = \frac{r}{\tau}\,\frac{m}{s} = \frac{r\rho w}{2\tau}$$

is the absorption per unit surface area. Solving equation (2) for v yields

$$v = \left(\frac{2q}{s}\right)^2 \frac{1}{\phi^2}\,\frac{d}{k'}\,.$$

Setting the absorption at $q/s = 10^{-10}$ g sec⁻¹ cm⁻², $\phi = 3.1\text{x}10^{-8}$ g cm⁻³ (1 μg-at P/l), $d = 4$ cm, yields $v = 37$ cm/sec. If the nutrient concentration is reduced to 0.5 μg-at P/l, $v = 150$ cm/sec. It would appear that attached plants must obtain their nutrients from the sea bottom or a bacterial slime film, or otherwise exist in an environment rich in nutrients and exposed to high velocities such as are found in shallow

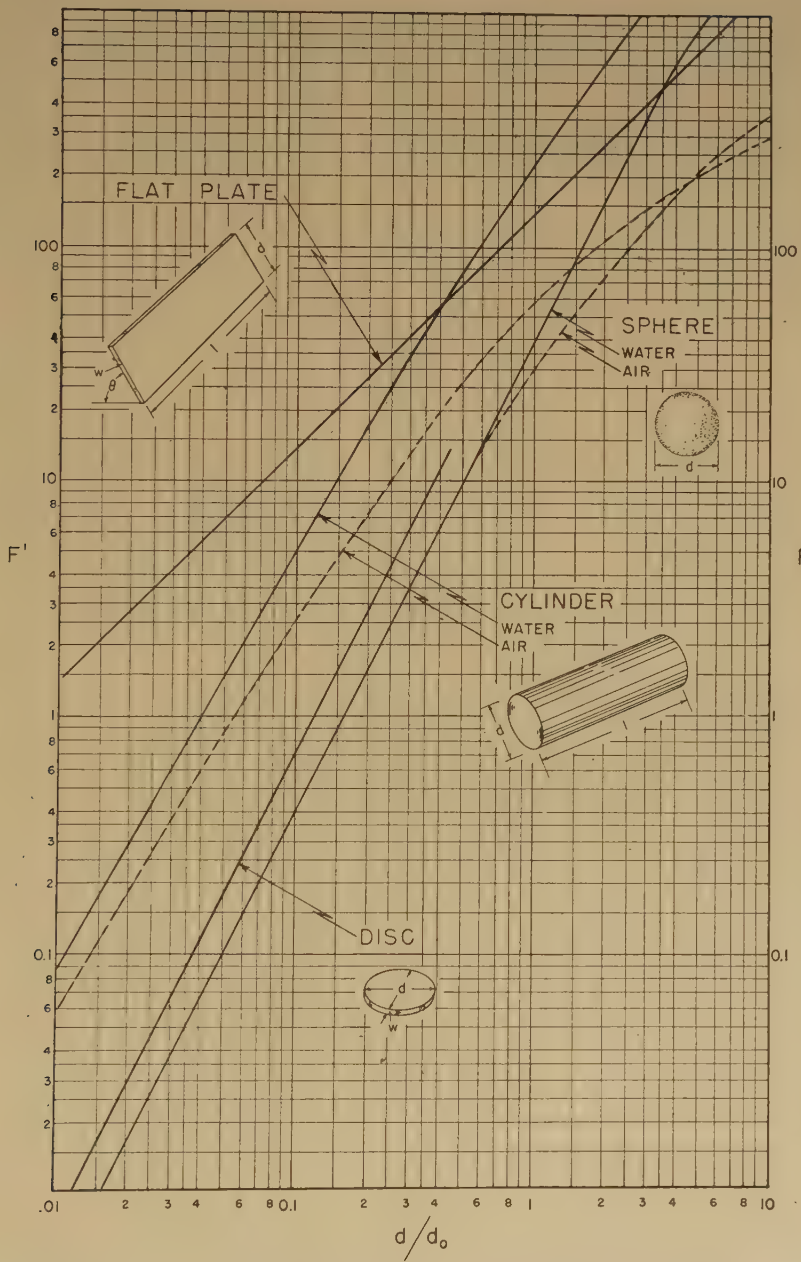

Figure 2. Plot of the relative sinking rate, F', as function of the diameter, d, for the various geometric shapes considered in Fig. 1. The curves are based on both theoretical and experimental considerations.

water along open coast lines. Unattached plants can meet their nutrient requirements by being small, as will be shown next.

4. SINKING PLANTS

The curves in Fig. 1 show the effect of size on absorption time. For any given form and shape (w/d constant), the absorption time always increases with increasing size. As far as absorption of nutrients is concerned, small size is therefore always an advantage. This factor is, of course, only a part of a complex problem which involves the merits of structural differentiation, the predator-prey relationships, etc.

Let the slope of the curves be denoted by

$$m = \frac{d \log F}{d \log x}, \tag{8}$$

where $x = d/d_0$. For the plate, $m_p = -1$. This means that the *absorption rate per unit mass is doubled when the dimension d is halved.* For cylinders, $m_c = -1.2$. For large spheres, $m_s - 1.1$; for small spheres, $m_s = -2.0$. The advantage of small size is most pronounced for small spheres. The change in slope[6] of the curve for spheres represents a marked change in the advantage of small size for spheres smaller than d_0 as compared to spheres larger than d_0. It may be significant that, in the case of water, d_0 is roughly 0.01 cm (100 μ), a value fairly representative of the diameter of diatoms.

In the case of sinking plates, the absorption time varies as $w^{2/3} d^{1/3}$. It is remarkable how much more effectively the production of organic material is increased by splitting as compared to dividing lengthwise (in the direction of flow). Splitting increases τ^{-1} by $2^{2/3}$, dividing by $2^{1/3}$. The number of diatoms resulting from a single diatom by dividing after n generations is 2^n. In the same time interval the splitting diatoms will have gone through $2^{1/3} n$ generations, and the number of diatoms will equal $2^{2^{1/3}n}$. The ratio $2^{(2^{1/3}-1)n}$ equals 100 after 25 generations.

A few examples will illustrate the application of the formulae and the kind of information they provide on the problems of diatom existence. Assume an array of diatoms approximating the ideal shapes of spheres,[7] discs, and long cylinders and plates in which the dimension

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[6] The physical interpretation of this change in slope is that for $d \ll d_0$ absorption is largely by diffusion, whereas for $d \gg d_0$ absorption is largely by forced convection. An increase in size leads to a smaller surface/volume ratio, and this is always unfavorable. In the case of convection, however, some of the disadvantage is offset by an increase in the sinking rate.

[7] While true spheres are rare, the specifications will be closely approximated by discs in which the thickness equals the diameter and perhaps also by more irregular shapes such as *Biddulphia.*

d (Fig. 1) ranges from .0005 to .03 cm (5 to 300 μ). Let the ratio of diameter to thickness in the discs be 3:1 and of width to thickness in the plates 5:1. The angle of the plate is 10°. Phosphorus is designated as the limiting nutrient, and its concentration r in the diatom is assumed to be .001 (based on the estimate that phosphorus constitutes about 1% of the total organic matter and that the latter is about 10% of the wet weight).

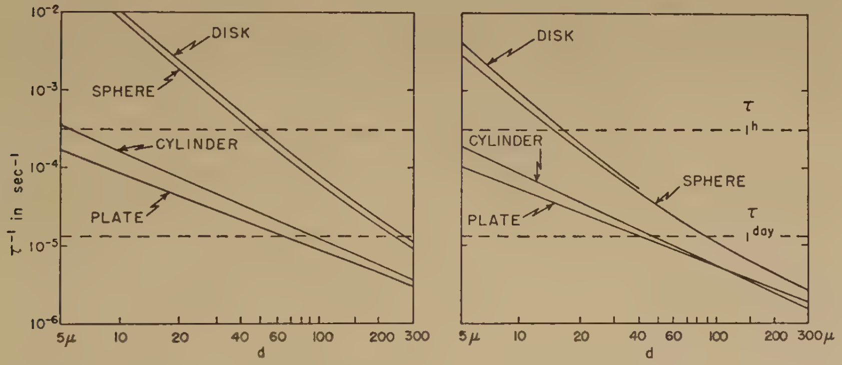

Figure 3. Absorption rates τ^{-1} (in sec^{-1}) for bodies of various sizes d (in μ) corresponding to example 1 (left) and example 3 (right).

Example 1. In well fertilized laboratory media, diatoms generally have a nearly negligible sinking rate. A similar condition may exist in the sea during flowerings. To simulate this condition in the model, let $\Delta\rho/\rho = .0001$; $\phi = 3.1 \times 10^{-8}$ g cm^{-3} (1 μg-at P/l). This gives $d_0 = 0.052$ cm, $v_0 = 3.8 \times 10^{-4}$ cm sec^{-1}, according to equations (7). For a sphere in water with $d = 0.01$ cm (100 μ), we find $d/d_0 = 0.19$, and hence $F_s = 19$, $F_s' = 1.5$, according to Figs. 1 and 2 respectively. From equation (5) we obtain $\tau^{-1} = 7.1 \times 10^{-5}$ sec^{-1}, or $\tau = 4$ hours; from (5a) $v = 5.6 \times 10^{-4}$ cm sec^{-1}, or 2 cm/hour. The computed absorption rates are plotted in Fig. 3 (left). They set a maximum limit to the size of diatoms that can absorb sufficient phosphorus to maintain an adequate division rate. For example, one division per day ($\tau^{-1} = 1.16 \times 10^{-5}$) requires that the width of a plate shall not exceed 76 μ and that the diameter of spheres, discs and cylinders shall not be greater than 260, 300, and 105 μ respectively. More than 90% of the marine diatom species fall within the prescribed maximum limits. Larger sizes require further reductions in specific gravity in order to maintain negligible sinking rates, and nutrient absorption then requires an increase in ϕ or a decrease in r.

Example 2. If ϕ is reduced to 3.1×10^{-9} g cm^{-3} (0.1 μg-at P/l) and other conditions remain the same, the value of τ^{-1} in Fig. 3 (left) will be reduced one order of magnitude. Plates and cylinders capable of maintaining one division per day will then have a maximum dimension d of less than 10 μ. Spheres and discs will have maximum diameters of 61 and 65 μ respectively. These are unrealistic results, particularly for plates and cylinders. Larger species have been observed in the sea under conditions of severe nutrient depletion.

Example 3. ϕ remains 3.1×10^{-9} g cm^{-3}. Let $\Delta\rho/\rho$ increase to .02; i. e., the specific gravity of the diatoms is now about 1.045. Unfortunately the flat disc can no longer be included in the calculation, since the value of d/d_0 exceeds the limits of the curve in Fig. 1. The other calculations are illustrated in Fig. 3 (right). The relative effectiveness of plates and cylinders is now greatly increased. The maximum size permitting one division per day ranges between 48 and 95 μ in the different groups.

The change is due of course to the fact that the increase in specific gravity increases the sinking rate and thereby accelerates nutrient absorption. It should be pointed out in this connection that nutrient depletion in experimental cultures is commonly accompanied by an increased sinking rate. The same phenomenon may occur in the sea toward the end of a flowering and perhaps throughout the summer. There may be an increase in specific gravity due to the accumulation of storage products that cannot be used for reproduction because of nutrient deficiency. If so, we can postulate a self-regulatory device, since the accumulation of storage products will automatically increase the rate of nutrient absorption. However, the value of such a device is limited. It serves no useful purpose if the sinking rate is rapid enough to carry the diatoms below the euphotic zone before the necessary cell divisions occur. The calculated sinking speeds shown in Fig. 4 are by no means negligible for the larger size categories. Thus it becomes necessary to include the problem of flotation in the solution of the example.

It should be pointed out that values for $\Delta\rho/\rho$ have been so chosen as to yield realistic results with regard to absorption rates. These values of $\Delta\rho/\rho$ may be regarded as minimum values; if they were smaller it would be impossible to reconcile the computed absorption rate with the observed rate of division. In this regard it can be noted that the minimum value under natural conditions (example 3) is several hundred times the value corresponding to well fertilized laboratory media (example 1). Values of $\Delta\rho/\rho$ can be larger than those given. In that case conditions other than nutrient absorption must be limiting the

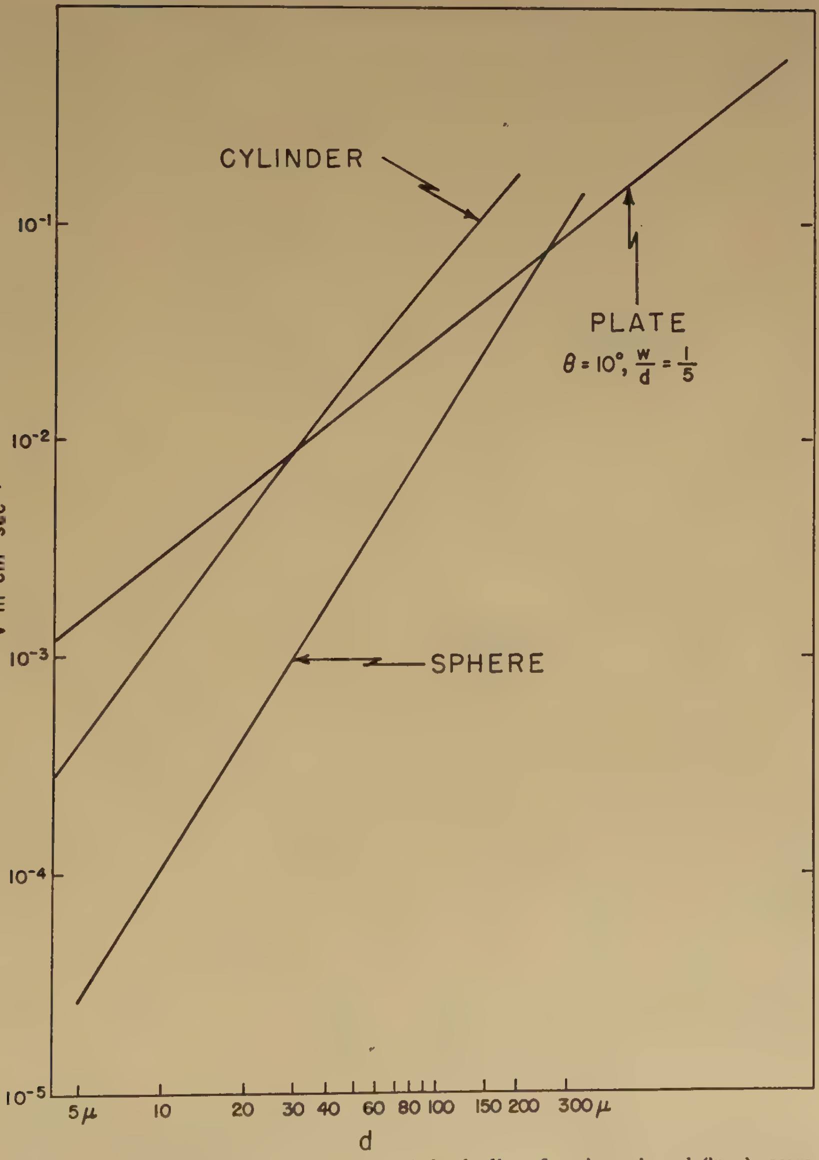

Figure 4. The sinking speed v (in cm sec^{-1}) for bodies of various sizes d (in μ), corresponding to example 3, with $\Delta\rho/\rho = 0.02$.

rate of division. Apparently values of $\Delta\rho/\rho$ cannot be very much larger, or they would lead to unrealistic sinking rates. For the purpose of this paper we shall develop the implications of the hypothesis that nutrient absorption is one limiting factor. Our evidence does not permit us to say whether this is usually, or even sometimes, the case. On the other hand, there is nothing in our quantitative results that would make this hypothesis difficult to maintain.

5. THE FLOTATION PROBLEM

Perhaps the simplest way to analyze the flotation problem is to make use of a theoretical relationship derived by Riley, Stommel, and Bumpus (1949: 90). It postulates that a steady state, nonvanishing plankton distribution cannot occur if $v^2 > 4A\omega$, where v is the sinking speed, A is the coefficient of vertical eddy diffusivity, and ω is the mean coefficient of production in the euphotic zone.

Other factors may enter the situation and require a lesser sinking speed, but for present purposes it is sufficient to assume that equality exists in the steady state condition. In addition to the sinking speeds in Fig. 4, the analysis requires that we stipulate reasonable values for the eddy coefficient and utilize the calculated nutrient absorption rates to estimate the mean production coefficient ω. The latter was originally defined as the net production coefficient, i. e., diatom multiplication minus predation. In the first approximation we shall assume that predation is negligible, but we shall have to revise the assumption subsequently in Section 6.

The following considerations enter into the calculation of ω:

1. Although the absorption curves in Fig. 3 (right) theoretically permit the small cells to divide many times per day, there exists an inherent biological limit that cannot be surpassed. We shall simplify the situation by assuming that when nutrients are not limiting, the maximum production coefficient, occurring in the upper 20% of the euphotic zone, is 2.32×10^{-5}/sec (two divisions per day).

2. It will be assumed that in the remainder of the euphotic zone the limiting effect of light produces an exponential decrease with depth to 1% of the surface value. The resulting curve for maximum production is shown as a solid line in Fig. 5 (left).

3. When lack of nutrients reduces surface production, the form of the curve is assumed to change as shown by the dotted line in Fig. 5 (left). Fig. 5 (right) shows the relationship between surface and mean production that results from these assumptions.

Thus Figs. 3 (left) and 5 (left) may be used to estimate the mean production coefficient ω for various sizes and shapes of cells. Examples are given in Table II, which also lists a critical coefficient ω':

TABLE II. PRODUCTION COEFFICIENTS

d	*Sphere*			*Cylinder*			*Plate*		
μ	$10^6\,\omega$ sec^{-1}	$10^6\,\omega'$ sec^{-1}		$10^6\,\omega$ sec^{-1}	$10^6\,\omega'$ sec^{-1}		$10^6\,\omega$ sec^{-1}	$10^6\,\omega'$ sec^{-1}	
		A (cm^{2}sec^{-1})			A (cm^{2}sec^{-1})			A (cm^{2}sec^{-1})	
		10	50		10	50		10	50
5	9.2	$1.8\text{x}10^{-5}$	$3.6\text{x}10^{-6}$	9.2	$4.2\text{x}10^{-3}$	$8.4\text{x}10^{-4}$	9.2	$5.6\text{x}10^{-2}$	$1.1\text{x}10^{-2}$
10	9.2	$3.0\text{x}10^{-4}$	$6.0\text{x}10^{-5}$	9.2	$4.9\text{x}10^{-2}$	$9.8\text{x}10^{-3}$	9.2	$2.2\text{x}10^{-1}$	$4.4\text{x}10^{-2}$
20	9.2	$4.8\text{x}10^{-3}$	$9.6\text{x}10^{-4}$	9.2	$5.1\text{x}10^{-1}$	$1.0\text{x}10^{-1}$	9.2	$9.0\text{x}10^{-1}$	$1.8\text{x}10^{-1}$
30	9.2	$2.5\text{x}10^{-2}$	$5.0\text{x}10^{-3}$	8.9	2.2	$4.4\text{x}10^{-1}$	7.8	2.0	$4.0\text{x}10^{-1}$
40	9.2	$8.1\text{x}10^{-2}$	$1.6\text{x}10^{-2}$	7.3	5.6	1.2	6.6	3.6	$7.2\text{x}10^{-1}$
50	9.2	$2.0\text{x}10^{-1}$	$4.0\text{x}10^{-2}$	6.1	11	2.2	5.6	5.6	1.1
60	9.2	$4.2\text{x}10^{-1}$	$8.4\text{x}10^{-2}$	5.3	20	4.0	4.9	8.1	1.6
70	8.0	$7.8\text{x}10^{-1}$	$1.6\text{x}10^{-1}$	4.7	32	6.4	4.4	11	2.2
80	7.0	1.3	$2.6\text{x}10^{-1}$	4.2	48	9.6	4.1	14	2.8
90	6.3	2.2	$4.4\text{x}10^{-1}$	3.9	73	15	3.8	18	3.6
100	5.6	3.3	$6.6\text{x}10^{-1}$	3.5			3.5	22	4.4
150	3.7	17	3.4	2.5			2.6	50	10
200	2.9	58	12	1.9			2.0		

$$\omega' = \frac{v^2}{4A}.$$

When ω exceeds ω', the cells will increase unless predation is equal to the difference between the two quantities. When ω is less than ω', the species must vanish. Lines in Table II indicate approximately the maximum size of cells that can exist in a steady state condition ($\omega = \omega'$).

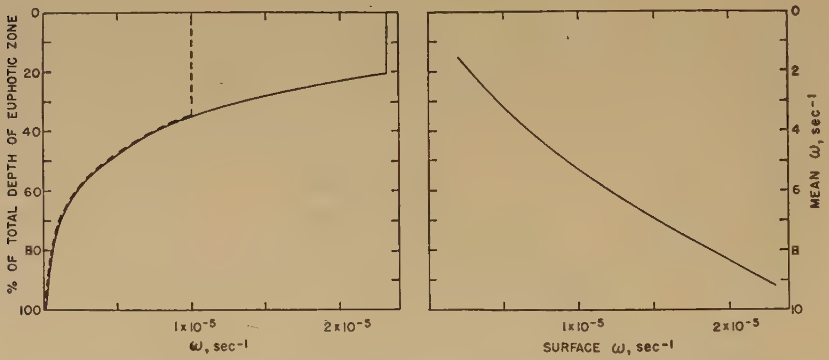

Figure 5. Left: Production coefficient as function of depth. Dashed line illustrates case where nutrient absorption limits production to 1 division in 10^5 seconds in upper 35% of euphotic zone, and the light intensity limits production in lower 65%. Solid line represents conditions for unlimited nutrient supply. Right: Relationship between surface production and mean production in euphotic zone.

The results serve only to specify maximum size limits. They reveal no good reasons for the evolution of the diatoms into a variety of shapes and sizes. Fig. 3 and Table II indicate that it is an advantage for them to be small. In all size categories, a primitive centric type approximating a sphere appears to be slightly superior to the more elaborate shapes.

6. THE GRAZING FACTOR

The fact that neither flotation nor nutrient absorption imposes severe limits upon cells of less than 20 μ must mean that some other factor is decidedly unfavorable. Otherwise the larger species would not be able to compete with the small cells. Predation is a possible explanation. Although it has been demonstrated (Harvey, 1937) that a large copepod such as *Calanus finmarchicus* feeds most effectively on large cells, it seems likely that the small animals which constitute the major bulk of the zooplankton population would have definite limits as to the size of the food they encompass. Therefore, two hypotheses are proposed: (a) The average predation coefficient decreases with an increase in the size of the food species; (b) the coefficient of predation on a sphere is larger than for a cylinder of the same diameter or for a plate of the same width.

An analysis of the hypotheses may be developed as follows:

1. Assume a diatom population of spheres, cylinders, and plates of varying sizes up to the maximum size that can maintain a steady state (cf Table II). In each size category, let the number of spheres, cylinders, and plates be initially equal.

2. Further assume that the total number of cells in the population has a steady state existence. This does not necessarily imply that any particular shape of cell exists in a steady state, but if, for example, the number of spheres of a particular size increases, there must be a corresponding decrease of plates or cylinders. The requirements of the first two assumptions will be fulfilled if, in each size category, the production coefficient equals the mean value of ω' (Table II) for the three shapes. This in turn requires that the predation coefficient equal the mean value of $\omega - \omega'$. The latter decreases with increasing size of the cells in accordance with hypothesis (a).

3. To fulfill hypothesis (b), a modification must now be introduced. It is arbitrarily assumed that the coefficient of predation on a cylinder of a given diameter and on a plate of the same width will be equal to the predation on a sphere with a diameter three times as large. This is readily accomplished in the model by comparing 10 μ cylinders and plates with 30 μ spheres, etc.

Thus in the two examples in Table II ($A = 10$ and $A = 50$ cm^2 sec^{-1}), positive values of $\omega - \omega'$ are averaged for each of the stipulated size groups. For each shape, the deviation of $\omega - \omega'$ from the mean is plotted in Fig. 6. Within the limits of the simplified assumptions, the deviations of each shape from the steady state existence of the population as a whole are indicative of the competition pressure exerted by a particular size and shape of diatom.

Cells of less than 20 μ show no striking differences in ability to compete. Within this range, competition must depend primarily upon factors that are not considered in the present analysis, namely inherent biological potentialities and reactions to the physical variations of the environment. In the larger size categories, cylinders appear to be particularly effective in the size range of 20 to 55 μ, plates from 30 to 95 μ. The spheroidal type appears to have a wider range of effectiveness than the other two shapes. In the present example it is not excessively dominant in any size category, but the form of the curve can be altered by changing assumption 3. If the spheres are compared with other shapes of half the size, instead of one-third, there is a strong peak of effectiveness centered at 60 μ.

7. COMPARISON WITH OBSERVED SIZE-FREQUENCY DISTRIBUTIONS

To determine whether these results have any meaning, we must inquire as to whether they bear any relation to observed diatom speciation. A list of species was prepared, more or less approximating the ideal shapes under consideration. The list will not be reproduced in detail, but the following genera were included:

Spheroids	Cylinders	Plates
Thalassiosira	*Rhizosolenia*	*Eucampia*
Coscinodiscus	*Lauderia*	*Climacodium*
Hyalodiscus	*Schroderella*	*Streptotheca*
Lauderia	*Dactyliosolen*	*Hemiaulis*
Stephanodiscus	*Leptocylindricus*	*Striatella*
Biddulphia	*Guinardia*	*Plagiogramma*
	Ditylum	*Pseudoeunotia*
	Cerataulina	*Achnathes*
22 species	31 species	11 species

Lauderia glacialis is placed among the spheroids, *L. borealis* with the cylinders.

The size limits of each species as listed by Cupp (1943) were then used to determine the size-frequency distribution of each shape, expressed as the percentage of the total number of species occurring in each size category. The results, plotted in Fig. 6, show that frequency modes of observed speciation correspond with favorable portions of the theoretical curves.

The large and important genus *Chaetoceros* is not included in the analysis. The individual species intergrade between plate-like and cylindrical form. The effect of the spines on its behavior is uncertain. However, examination of the genus shows a mode in the number of species at 12 μ, with less than 20% of the species in any size category above 35 μ. It could be placed with plates or cylinders without producing serious discord.

A small number of spheroids and cylinders (primarily *Coscinodiscus* and *Rhizosolenia*) greatly exceed the maximum size limits predicted by the example. They probably represent a special case that does not meet the initial assumptions. *Coscinodiscus* in particular has an unusually large vacuole, which probably gives it an abnormally low specific gravity and nutrient content. This appears on theoretical grounds to be virtually a necessity for large diatoms occurring in stable waters deficient in nutrients. For example, the 200 μ sphere in Table II requires an eddy coefficient of 200 cm^2 sec^{-1} in order to maintain

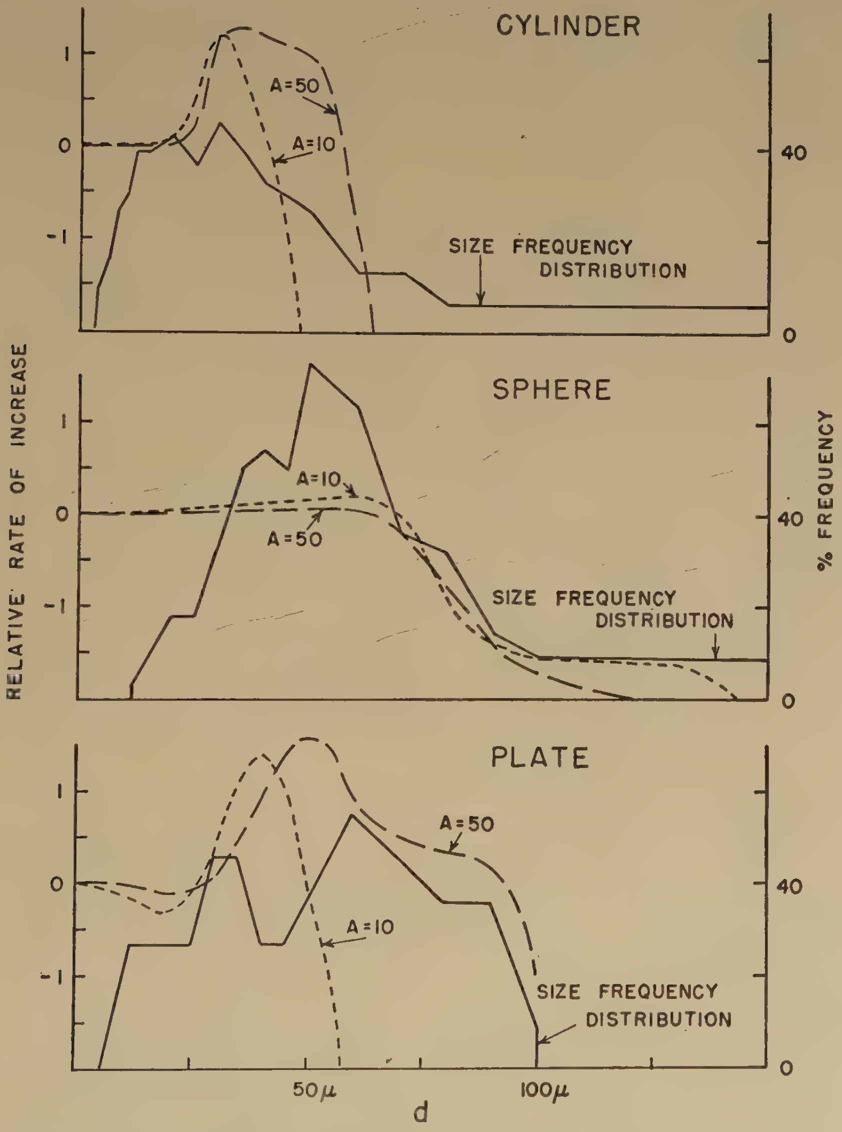

Figure 6. The dashed lines, corresponding to eddy viscosities of 10 and 50 cm² sec⁻¹, are indicative of the "competition pressure" exerted by diatoms of stated shapes and sizes. These curves are based on an analysis which takes into account nutrient absorption, the flotation problem (including sinking rates and vertical overturn), and the grazing factor. The solid curves give the observed size-frequency distribution for species resembling spheroids, cylinders, and plates, respectively.

a steady state in the absence of predation. If this cell is increased to a diameter of 300 μ solely by the addition of vacuolar space containing a fluid of the specific gravity and phosphorus content of the surrounding sea water, it will then be capable of maintaining a steady state in the absence of predation with an eddy diffusion coefficient of only 17 $\mathrm{cm}^2\ \mathrm{sec}^{-1}$.

In short, the analysis has revealed a situation too complicated to be tested easily by experiments or to be solved indisputably by theory. However, the calculated curves of competition pressure in relation to size and shape find some degree of support in the observable facts of nature. It seems likely that diatom speciation is the product of three essential ingredients—responses to problems of flotation, nutrient absorption, and predation. In large diatoms the chief problems are flotation and nutrient absorption, and adaptations that tend to reduce these difficulties have been noted. In small diatoms, predation appears to be more important, and it is common to find chain formation and elaboration of shape, which must be of some help in avoiding nauplii and other small predators. In the intermediate size range, the formation of chains is presumed to be advantageous from the standpoint of predation, but it tends to endanger flotation and nutrient absorption. Here some curious adaptations are found. *Thalassiosira* and some other genera succeed in forming chains without sacrificing the advantages of discoid shape. About half of the plate-like species form chains that are curved or twisted. This tends to impart lateral motion to the sinking cells, thus improving nutrient absorption without greatly affecting the vertical velocity.

8. THE EFFECT OF TEMPERATURE ON ABSORPTION

A change in temperature will effect the rate of absorption by varying the physical constants in the surrounding medium and possibly by changes inside the plankton. We shall consider the external effects only. These may be regarded as constituting a lower limit on the temperature effect.

By far the most important effect of temperature can be ascribed to variations in diffusion coefficient k and viscosity ν. In most substances the viscosity decreases with temperature by about 2.5%/°C whereas the diffusion coefficient *increases* by about the same amount:

$$\alpha = \frac{1}{k}\frac{dk}{dT} = -\frac{1}{\nu}\frac{d\nu}{dT} = 0.025\ (^\circ\mathrm{C})^{-1}\,.$$

The coefficients appear in the combination $(\nu k)^{1/3}$ in the parameter d_0, and the temperature effects of ν and k cancel in the first approximation.

The coefficients appear also in the constant τ_0^{-1} in the combination $k^{1/3}\ \nu^{-2/3}$. This leads to

$$\frac{1}{\tau^{-1}}\frac{d\tau^{-1}}{dT} = \frac{1}{\tau_0^{-1}}\frac{d\tau_0^{-1}}{dT} = \alpha \tag{9}$$

for sinking plates, spheres and cylinders alike. Goldberg's[8] very rough estimate on the basis of his experiments is a factor of 5–10%/°C, i. e., from 2 α to 4 α. According to (9) the maximum absorption rate in the tropics might be roughly twice that in the arctic. Similar results have been obtained in studies of the photosynthesis and growth of natural phytoplankton populations (Riley, Stommel and Bumpus, 1949: 94).

9. THE EFFECT OF TURBULENCE AND NOISE ON ABSORPTION

In our discussion we have dealt with sinking through still water. Yet whenever suitable measurements have been made, it has been found that the ocean is in turbulent motion.

Turbulence enters the general problem in a number of ways: it brings about the replenishment of the nutrients in the euphotic zone, i. e., it affects the value of ϕ in our equation (1); large eddies help maintain the sinking diatoms in the euphotic zone (Section 5); turbulence also erases the tiny trails of impoverished water left behind the individual diatoms sinking through the water. These effects enter only indirectly into the problem concerning the absorption of nutrients by sinking diatoms.

Here we shall be concerned only with the effect of turbulence in increasing the volume of water with which plankton are in immediate contact. For this purpose turbulence can be regarded to include all the unsteady motion. This motion can be resolved into many different frequencies. Low frequencies, with periods of, say, 10 seconds, are due largely to ocean waves (whether the waves are regular or not is of no consequence here); noise in the sea is associated with frequencies above 100 cycles/sec. Consider now a small sphere slowly sinking through water. The sphere can follow low frequency oscillations of the surrounding water without appreciable lag. However, with increasing frequency a condition is reached where the sphere is no longer able to follow the water motion without lag. For even higher frequencies the sphere will remain virtually stationary, while the water will wash back and forth along its sides. Such high frequency turbulence is therefore associated with a "forced draft" which can be expected to increase the nutrient made available to plankton.

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[8] Personal communication.

For any *fixed* amplitude of oscillation, the most effective forced draft is associated with the highest frequencies, i. e., acoustic noise. However, it is found that amplitude of oscillations in the ocean drops off so rapidly with increasing frequency that the most effective portion of the turbulence spectrum lies in the low frequencies. Even there, as will be shown, the effect is quite small.

TABLE III. VALUES OF PERTINENT PARAMETERS

	Surface waves	*Sound waves*	
Frequency $\sigma/2\pi$ in cycles per second	10^{-1}	10^{2}	10^{4}
Wave length L in cm	15,000	1500	15
β for $d = 10^{-2}$cm (100μ)	$2\text{x}10^{-6}$	$2\text{x}10^{-5}$	$2\text{x}10^{-3}$
γ for $d = 10^{-2}$cm (100μ)	0.03	0.9	9

The theory is rather involved. Fortunately it is closely related to the problem of the attenuation of sound by fog, which has received the attention of the mathematicians and experimentalists (Epstein, 1941). Let us define the ventilation

$$h = \frac{v_{water} - v_{sphere}}{v_{Stokes}}$$

as the ratio between the mean slippage through the water associated with turbulence, and the sinking velocity v_{Stokes} according to Stokes' law. The slippage depends on three dimensionless quantities,

$$\frac{\Delta\rho}{\rho}, \quad \beta = \frac{\pi d}{L}, \quad \gamma^2 = \frac{\sigma d^2}{8\nu},$$

where L is the wave length, σ frequency, and $C = L\sigma/2\pi$ the wave velocity. Some values of β and γ are given in Table III. It appears that γ may be large or small compared to unity but that $\beta \ll 1$. In addition $(\Delta\rho/\rho) \ll 1$. With these approximations it can be shown (Appendix 2) that

$$h = \frac{48\nu}{\pi g d^2} f(\gamma) V, \tag{10}$$

where

$$f = \gamma^2/3, \qquad\qquad f = \tfrac{1}{2},$$

according to whether the frequency is small ($\gamma \ll 1$) or large ($\gamma \gg 1$). Here V is the amplitude of the velocity of oscillation of the water.

Surface Waves. For very low frequencies equation (10) gives the ventilation arising from the viscous effects only. This can be used to analyze the effect of surface waves whose height H equals $2V/\sigma$, and wave length $L = 2\pi g/\sigma^2$. Equation (10) then becomes simply

$$h = 2H/L.$$

The theoretical maximum for H/L equals 1/7 and leads to $h = 0.28$. This value is attained only under extreme conditions; furthermore it applies only to a thin upper layer of thickness, say $L/10$, and diminishes rapidly with increasing depth. Thus under extreme conditions the absorption may be increased by something like 25% in the upper 10 or 20 feet.

Noise. For ambient sound it is convenient to convert the amplitude of oscillation to pressure amplitude P and express these in the customary units (see, for example, Knudsen and Harris, 1950). Thus

$$V = \frac{P}{\rho C}, \qquad P = \frac{1}{5000} 10^{L'/20},$$

where L' is the sound level in *db*'s above 0.002 dynes cm^{-2}. Measurements of ambient noise (Knudsen, et al., 1948) are well represented by straight lines on a graph L' against log σ, such as

$$L' = 20\,a - 20\,b \log(\sigma/1000)\,.$$

This leads to

$$\delta h = \frac{48\,\nu\, f(\gamma)}{5000\,\pi\rho g C d^2} 10^{a+3b}\,\sigma^{-b}\,\delta\sigma$$

for each frequency band $\delta\sigma$. We shall overestimate the effect by setting $f(\gamma) = \frac{1}{2}$. Integrating from σ_1 to σ_2, this gives

$$h = h_0 \frac{10^{a+3b}}{1-b}\left(\sigma_2{}^{1-b} - \sigma_1{}^{1-b}\right),$$

where

$$h_0 = \frac{24\,\nu}{5000\,\pi\rho g C d^2}$$

equals 10^{-9} for $d = 0.01$ cm ($100\,\mu$).

For ordinary water noises from 100 to 25,000 cycles, $a = 2.25, b = 0.8$. Since $1 - b$ is positive, the larger contribution is made by the higher frequencies. Between the stated limits, this gives $h = 10^{-3}$.

In a very noisy croaker bed one may set $a = 4$, $b = 0$ from $\sigma = 10^2$ to 10^3 sec^{-1}, and $a = 4$, $b = 3$ from 10^3 to 10^4 sec^{-1}. These values lead to $h = 10^{-2}$ for either range of frequencies. The effect of ambient noise is therefore negligible.

APPENDIX I: DERIVATION OF ABSORPTION RATES

The three nondimensional numbers that are encountered in problems of forced convection are the Reynolds, Prandtl, and Nusselt numbers

$$Re = \frac{vd}{\nu} \qquad Pr = \frac{\nu}{k} \qquad Nu = \frac{9d}{ks\phi}. \tag{11}$$

In some texts the Péclet number $Pe = Re\,Pr$ is referred to. Here v is the velocity at large distances, ν the kinematic viscosity, k the diffusivity, q the grams of a concentrate transferred each second to an immersed body of surface area s, ϕ the concentration at large distances over that at the surface of the body (in g cm^{-3}), and d a representative dimension of the body. Let p be the volume, ρ the density, and $m = \rho p$ be the mass of the body. Then equation (1) can be written

$$\tau^{-1} = \frac{\phi}{r\rho}\,\frac{ks}{vd}\,Nu = \frac{\phi}{r\rho}\left(\frac{\Delta\rho}{\rho}\right)^{2/3}\tau_0^{-1}\,GF, \tag{12}$$

where

$$G = sd/cp \tag{13}$$

depends on the geometric dimensions, and

$$F = 72^{-2/3}\,c\,Nu(d/d_0)^{-2}. \tag{14}$$

The constant c is so chosen as to make G a ratio of dimensions only.

With regard to sinking rate, it is convenient to define a quantity $u_0 = k/d_0$. Then it follows from (11) that

$$\frac{u}{u_0} = \frac{Re\,Pr}{d/d_0}. \tag{15}$$

Attached Plate. This problem has been studied theoretically by Pohlhausen with regard to a flat plate thermometer oriented parallel to flow (Goldstein, 1938: Chap. 14). For one side of the plate

$$Nu = 0.67\,Pr^{1/3}\,Re^{1/2}, \tag{16}$$

where d in the Reynolds number now represents the length of a thin plate in the direction of flow. The equation has been verified experimentally. For the dimension as given in Fig. 1, substitution of (16) into (1) leads at once to equation (2).

Sinking Plate. The quantity v is no longer an independent variable but equals the sinking speed. Consider the plate slicing obliquely downward and forming an angle θ with the horizontal (Fig. 1). Then after the plate has reached its terminal velocity, the frictional forces on its sides is balanced by the pull of gravity:

$$2Tld = g\sin\theta\,\Delta\rho\,lwd,$$

where T is the frictional stress per unit surface area and $\Delta\rho$ the density of the diatom minus the density of the surrounding medium. The stress can be equated to

$$T = \nu\rho\left(\frac{dv}{dy}\right)_{y=0} = 2v\nu\rho\frac{2}{5.83}\sqrt{\frac{v}{\nu d}}$$

according to Von Kármań's boundary layer theory (Goldstein, 1938: Chap. 4). This leads to the dimensionless expression

$$\begin{aligned} Re^{3/2} &= 0.73(\Delta\rho/\rho)g\sin\theta\, wd^2\nu^{-2} \\ &= (0.73)(72)\sin\theta\,(w/d)\,Pr^{-1}(d/d_0)^3 \quad (17) \end{aligned}$$

for the sinking rate $v = Re\ \nu/d$ along an axis inclined by an angle θ. Combining equations (13) to (17) leads to

$$\begin{aligned} G_p &= (d^2\sin\theta/w^2)^{1/3}\,, \\ F_p &= (1.34)(0.73)^{1/3}(72)^{-1/3}(d/d_0)^{-1} = 0.29(d/d_0)^{-1}\,, \\ F_p' &= (0.73)^{2/3}(72)^{2/3}(d/d_0) = 14(d/d_0). \end{aligned}$$

Sinking Sphere. For Pr from 0.7 to 400 and Nu from 10 to 40, the following relationship is in agreement with experimental evidence and dimensional considerations (Kramer, 1946):

$$Nu = 2.0 + 1.3\,Pr^{0.15} + 0.66\,Pr^{0.31}\,Re^{0.15}\,. \qquad (18)$$

Note the combination $Pr^{0.31}\ Re^{0.5}$, which is similar to the one encountered for the flat plate. For water and air this becomes, respectively

$$Nu = 5.3 + 4.6\,Re^{0.5} \qquad (18w)$$

$$Nu = 3.3 + 0.66\,Re^{0.5}\,. \qquad (18a)$$

In these experiments the rate of flow past the sphere, as expressed by Re, could be varied independently. For freely falling spheres, it is already determined by the balance between the gravitational force and the drag:

$$\frac{1}{6}\pi\,\Delta\rho\,gd^3 = \frac{1}{2}C_D\,\rho v^2\left(\frac{\pi d^2}{4}\right).$$

The drag coefficient in the range over which Stokes' law is applicable equals $C_D = 24\ Re^{-1}$. We shall write, in general,

$$C_D = 24\,Re^{-1}f_s\,, \qquad (19)$$

where the function $f_s(Re)$ can be taken from experimental data (Goldstein, 1938: 493). This leads to the dimensionless expression

$$f_s\,Re\,Pr = 4(d/d_0)^3 \qquad (20)$$

for the sinking rate $v = \nu\ Re/d$ of a freely falling sphere. Thus $F_s' = 4(d/d_0)^2/f_s$. The absorption rate for the sphere (eq. 5) is now obtained in the following manner: in eq. (13) we set $s = \pi d^2$, $p = \pi d^3/6$, and $c = 6$. This leads to $G_s = 1$, and

$$F_s = 6 \times 72^{-2/3}\, Nu (d/d_0)^{-2} = 0.345\, Nu (d/d_0)^{-2} \,. \qquad (21)$$

We then substitute for Nu in terms of Re according to (18) and for Re in terms of d/d_0 according to (20).

For small values of $Pe = Re\, Pr$, Kronig and Bruijsten (1951) obtain from theory[9]

$$Nu = 2 + \frac{1}{2} Pe + \frac{581}{1920} Pe^2 + \ldots \qquad (22)$$

The empirical and experimental curves are shown in Fig. 1.

Sinking Disc. According to Oberbeck (Lamb, 1932: 597–604), $Nu = 8/\pi$ for a disc at rest. This compares to $Nu = 2$ for a resting sphere. Setting $s = \pi d^2/2$, $p = w\pi d^2/4$, and $c = 2$ gives $G_d = d/w$ and $F_d/F_s = 4/3\pi$. This ratio applies only to small discs (Fig. 1). We know of no empirical or theoretical evidence which would permit us to extend these calculations into a more pertinent range.

In computing the sinking rate of a small disc, we note that, according to theory and observations, small (but not too small) objects sink with the flat side horizontal. Equating the resistance to the force of gravity,

$$6\pi\,\mu \left(\frac{4d}{3\pi}\right) v = \pi \left(\frac{d}{2}\right)^2 w\, \Delta\rho\, g$$

leads to

$$Re\, Pr = \frac{9\pi}{4} \frac{w}{d} \left(\frac{d}{d_0}\right)^3$$

for the sinking speed. This yields $F_d' = (9\pi/4)(d/d_0)^2$.

Sinking Cylinder. Because of the relative ease with which measurements can be made with fine wires, the empirical evidence is more complete than for other shapes. For $Re > 50$, Ulsamer (Kramer, 1946) finds

$$Nu = 0.60\, Pr^{0.31}\, Re^{0.5} \,. \qquad (23a)$$

The occurrence of $Pr^{0.31}\, Re^{0.5}$ should be noted. For Re from 0.1 to 50, Ulsamer finds, on the average,

$$Nu = 0.91\, Pr^{0.31}\, Re^{0.385} \,. \qquad (23b)$$

At $Re = 0.1$, $Nu \sim Re^{0.3}$ approximately. There is also some theoretical evidence that, for very small Reynolds numbers, Nu should be a function of $(Pr\, Re)$ only, hence the exponent of Re would approach 0.31. Apparently we shall not be far amiss if we set

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[9] See footnote 10 on p. 240.

$$Nu = 0.8\,Pr^{0.31}\,Re^{0.31} \tag{23c}$$

for $Re \ll 1$. For the long cylinder (unlike the sphere), Nu must approach zero as Re approaches zero, in agreement with the foregoing type of equations. These three equations (23) define the relationship $Nu(Re)$ with sufficient accuracy for our purposes.

We can again express the sinking rate in nondimensional form. Using the relationships given by Lamb (1932: 616) we obtain

$$\frac{Re\,f_c\,Pr}{\kappa - \ln Re} = \frac{9}{2}\left(\frac{d}{d_0}\right)^3,$$

where

$$C_D = \frac{8\pi f_c}{Re(\kappa - \ln Re)}$$

is the drag coefficient, and $f_c(Re)$ can again be determined from empirical data (Goldstein, 1938: 16). For $Re \ll 1$, Oseen's investigations (Lamb, 1932: 616) lead to $f_c(Re) = 1$. Here $\kappa = 0.5 + \log 8 - \eta = 2.00$, and $\eta = 0.577$ is Euler's number. Setting $s = \pi d$, $p = \pi d^2/4$, and $c = 4$ gives $G_c = 1$, and

$$F_c = 4 \times 72^{-2/3}\,Nu\,(d/d_0)^{-2} = 0.23\,Nu\,(d/d_0)^{-2}. \tag{25}$$

We then substitute for Nu in terms of Re according to (23) and for Re in terms of d/d_0 according to (24).

APPENDIX II.

The ratio "R" between the displacement of a rigid sphere of density $\rho + \Delta\rho$ to that of the water (density ρ) at the position of its center when the sphere is absent is given by (Lamb, 1932: 659–661)

$$R = 1 - \frac{\Delta\rho}{\rho f' + \Delta\rho}, \tag{26}$$

where

$$f' = \frac{3}{4\gamma^2}\left[2\gamma^2 + 3\gamma - i\,(4\beta\gamma + 3\gamma + 3)\right]. \tag{27}$$

According to Table II, $\beta \ll 1$. Furthermore, $\beta \ll \alpha$, provided $2\nu\sigma/C^2 \ll 1$ or $\sigma \ll 10^{12}$ sec^{-1}. The simplifications resulting from these approximations have been incorporated in equations (26) and (27).

The following extreme cases should be noted:

1. The sphere oscillates essentially with the surrounding water ($R = 1$) (a) if its density equals that of the surrounding water ($\Delta\rho = 0$), (b) for low frequencies ($\sigma = 0$, $\beta = 0$), (c) for small spheres ($d = 0$, $\beta = 0$), and (d) for very viscous fluids ($\nu = \infty$, $\gamma = 0$). 2. The sphere does

not partake in the oscillation of the surrounding water ($R = 0$) if its density is large ($\Delta\rho = \infty$).

If $\Delta\rho \ll \rho$, $R = 1 - \Delta\rho/\rho f'$, then the mean value of $v_{sphere} - v_{water}$ equals

$$\frac{2}{\pi} V \frac{\Delta\rho}{\rho} (f_r'^2 + f_i'^2)^{-1/2},$$

where f_r' and f_i' are the real and imaginary parts of f'. Combining this with Stokes' equation for a small sinking sphere leads to

$$f(\gamma) = \gamma^2(4\gamma^4 + 12\gamma^3 + 18\gamma^2 + 18\gamma + 9)^{-1/2}. \qquad (28)$$

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Footnote 10 (added in page proof). Prof. Paul Epstein has just drawn our attention to the fact that the method used by Kronig and Bruijsten (1951) leads to a divergent series, and that only the first two terms in equation (22) of Appendix I, p. 238, are correct. The third term should be $-\frac{1}{4} Pe^2 \ln(\frac{1}{2}\Gamma e^{1/4} Pe)$ instead of $+ (581/1920) Pe^2$, where $\Gamma = 1.781$ is Euler's number. Actually the numerical values and the curve in Fig. 1 are not appreciably affected by this correction.

RECENT HISTORY OF A SAND SPIT AT SAN NICOLAS ISLAND, CALIFORNIA

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RECENT HISTORY OF A SAND SPIT AT SAN NICOLAS ISLAND, CALIFORNIA[1]

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ABSTRACT

At the eastern end of San Nicolas Island a low triangular sand spit occurs. Changes in the configuration of the spit during the last one hundred years demonstrate that it is unstable. In the spit, sand has been supplied primarily by an east-flowing longshore current which moves along the northeastern coast of the island.

INTRODUCTION

San Nicolas Island, eight miles long and three miles wide, is sixty miles off the mainland of southern California (fig. 1). The long axis of the island is northwest-southeast, in the prevailing wind direction of the region. A low sand spit at the southeastern end has formed in response to wind and current. Charts and photographs made during the last century show that the spit has changed outline markedly on at least two occasions.

GENERAL CHARACTERISTICS OF THE SPIT

The spit is a sand feature roughly triangular in shoreline, with the southern side more concave than the northern. The deposit is over two miles long and at low tide the spit point is about one mile from the main island mass. The submerged portion is sinuous in plan and about a mile long. Waves approach the submerged segment from northwest and southeast and crash against one another —a most spectacular sight during periods of heavy swell. Width of the spit increases from a few feet at the tip to nearly half a mile at the island. Approximately half the spit is from 5 to 15 feet above low water. On the southern side nearest the island a shallow lagoon develops occasionally. The lagoon is completely cut off from the sea by a bar (fig. 2) and is filled only by occasional high waves from the south.

CHANGES DURING THE LAST CENTURY

In 1847, Kellett described a line of breakers extending a mile and three-quarters from the eastern end of the island. It therefore appears probable that the spit had, at that time, a configuration similar to that which it has today. In 1851 the first accurate chart of the area was published by the United States Coast and Geodetic Survey. This chart does not show a spit, but instead a rounded sandy area farther northwest (fig. 3). Despite the fact that this survey was published on a scale of 1:380,000, it is unlikely that a feature as prominent as the present-day spit could have been missed. The first detailed survey of the island was made in 1879 by the U. S. Coast and Geodetic Survey. The modern spit was not then in existence (fig. 3); on the contrary, the large, rounded sandy protruberance first indicated by the 1851 survey is shown in considerable detail. In 1879 several sounding lines across the area now occupied by the spit show water depths of two to seven fathoms. This striking change, which evidently occurred between 1847 and 1851, has caused Davidson (1889) to remark:

> "... (Kellett) ... also lays down breakers for a mile and three-quarters from the eastern point. It is probable that he has been misled by heavy current rips conflicting with the westerly swell; or it is possible there may

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[1] Contribution from the Scripps Institution of Oceanography, new ser., no. 585.

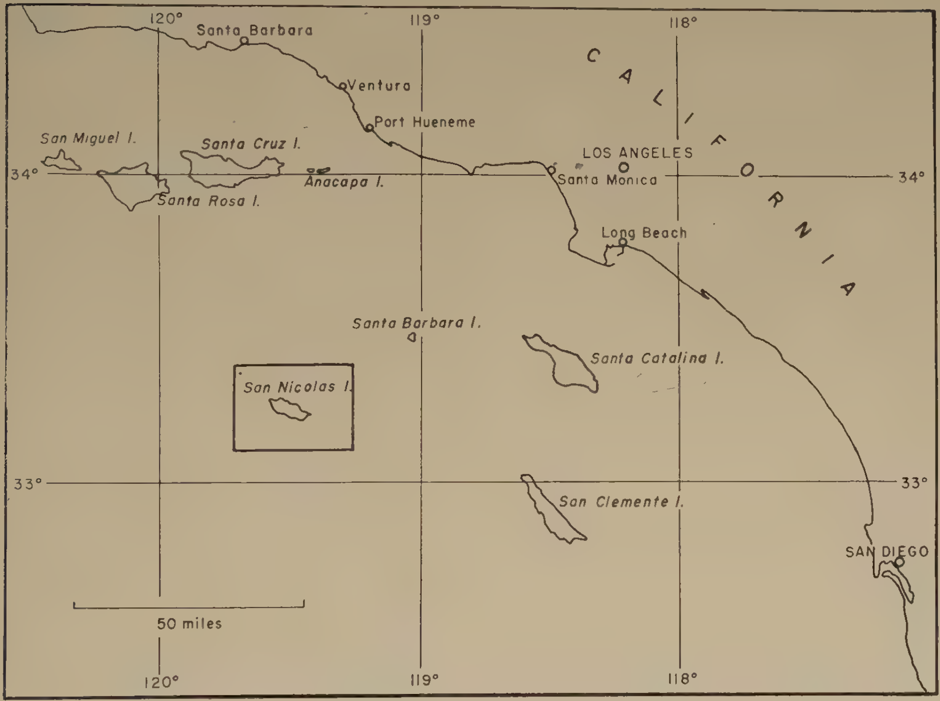
120°
119°
118°
Santa Barbara
Ventura
Port Hueneme
San Miguel I.
Santa Cruz I.
Anacapa I.
Santa Rosa I.
34°
LOS ANGELES
Santa Monica
CALIFORNIA
Long Beach
Santa Barbara I.
Santa Catalina I.
San Nicolas I.
33°
San Clemente I.
SAN DIEGO
50 miles

FIG. 1.—Outline map of southern California showing the location of San Nicolas Island.

be some hidden dangers in the kelp-field off the eastern end of the island . . . ."

Davidson, in the 1889 edition of the Pacific Coast Pilot, describes conditions as of that date:

> " . . . The eastern end of the island is one and one-quarter miles broad, high and bold, except at the northeast point, where there is a low sand spit stretching out one-third of a mile, and around which the currents run at times with great force . . . ."

Doubtless, Davidson referred to a feature like that shown on the 1879 chart (fig. 3), for the modern spit is not located at the northeastern extremity of the island, is much longer than a third of a mile, and currents certainly do not run "around" it. (The spit is pointed at its eastern end and a current would have to change direction nearly 180° in a very short distance in order to run "around" it.) Holder (1910) mentions: ". . . the long attenuated sand spit . . ." indicating that the present-day configuration had been attained by 1910.

A second detailed U. S. Coast & Geodetic chart was made in 1925, and a third in 1932. Airplane photographs were taken, in 1943 by Fairchild Aerial Surveys, Inc., in 1945 and 1950 by the United States Navy Electronics Laboratory, and in 1950 by the United States Marine Corps. Charts and photographs all show a long attenuated sand spit, differing only slightly in each case. These are compared in figure 3. The history of the sand spit suggests the feature is in delicate adjustment with its environment. Approximation of the volume of sand in the spit from 1851 to 1879 compares favorably with that of the present spit if it is assumed that the amount of sand below low water was the same in both cases. Unusual wave action from the south may have been responsible for the northward shift between 1847 and 1851.

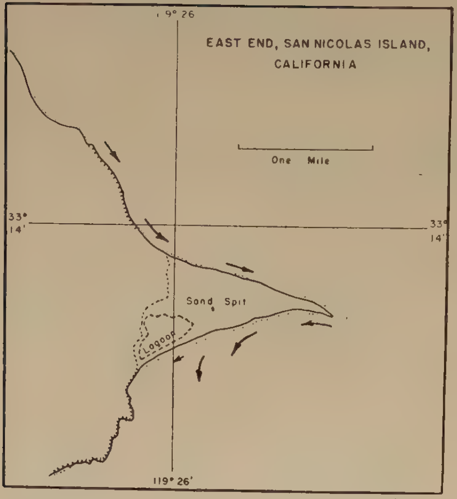

FIG. 2.—Detail of San Nicolas sand spit showing location of the lagoon and the direction of prevailing longshore currents.

Weather records do not extend far enough to show if the 1851 to 1879 position was maintained by more or less unusual wave activity from the south or whether the southward shift between 1879 and 1910 can be attributed to unusual waves from the northwest. In either case, it appears that the volume of sand in the spit is nearly static and that the feature moves as a unit.

SOURCE AND DEVELOPMENT OF THE SPIT

Wind plays a significant rôle in the maintenance of the spit, yet the spit is not primarily wind-formed. Prevailing winds are northwesterly and often blow vigorously for days at a time. Bottles and glass fish-net floats stranded on the spit are commonly sand-blasted on their windward sides and completely unaffected to the leeward. Low, parallel ridges of loose shifting sand lie obliquely across the spit, formed by winds blowing across, rather than parallel, to the spit. Troughs between these ridges are often covered with shell "pavement." Wind and surf, acting in concert, have heaped sand as much as 15 feet above low water. Locally, the process has been assisted by jetsam which holds some of the sand in place. Winds blowing parallel to, or approaching the northeast coast at a slight angle should produce a well-defined longshore drift. The southern coast, on the other hand, is parallel to prevailing wind direction only in its western half; the eastern half of the southern coast normally lies in the lee, and longshore drift is apt to be weaker there. Northwesterly winds have the least effect where the south side of the spit joins the main mass of the island. Here, the island rises boldly some six-hundred feet and protects the shore from all but the strongest winds.

Current measurements made along the northern coast confirm the existence of a strong longshore drift toward the spit (0.2 to 0.3 knot during a period of low waves). Near the outer extremity of the northern side of the spit, waves approached (March 1951) at an angle which should have developed a northwest-flowing current in opposition to the wind. The fact that this did not occur indicates that longshore drift established along the northern coast of the island had sufficient velocity to overcome opposing wave approach near the end of the spit. During a period of southern swell (March 1951), currents measured along the southern side of the spit moved westward toward the island, turning away from shore near the mid-point of the spit (fig. 2). This current and the one on the north side of the spit evidently act to maintain the *status quo* by carrying excess sand into deeper water.

The spit is believed to be primarily the product of sand drifted along the northern coast of the island for the following reasons:

(1) Longshore drift is well-developed along the northern coast and acts in the proper direction. Further, the northern side of the spit is nearly a continuation of the north coast beaches, whereas the southern side is offset from the general trend of the southern coast, and is separated from the southern beaches by a large rocky headland (fig. 3).

(2) Longshore drift on the southern

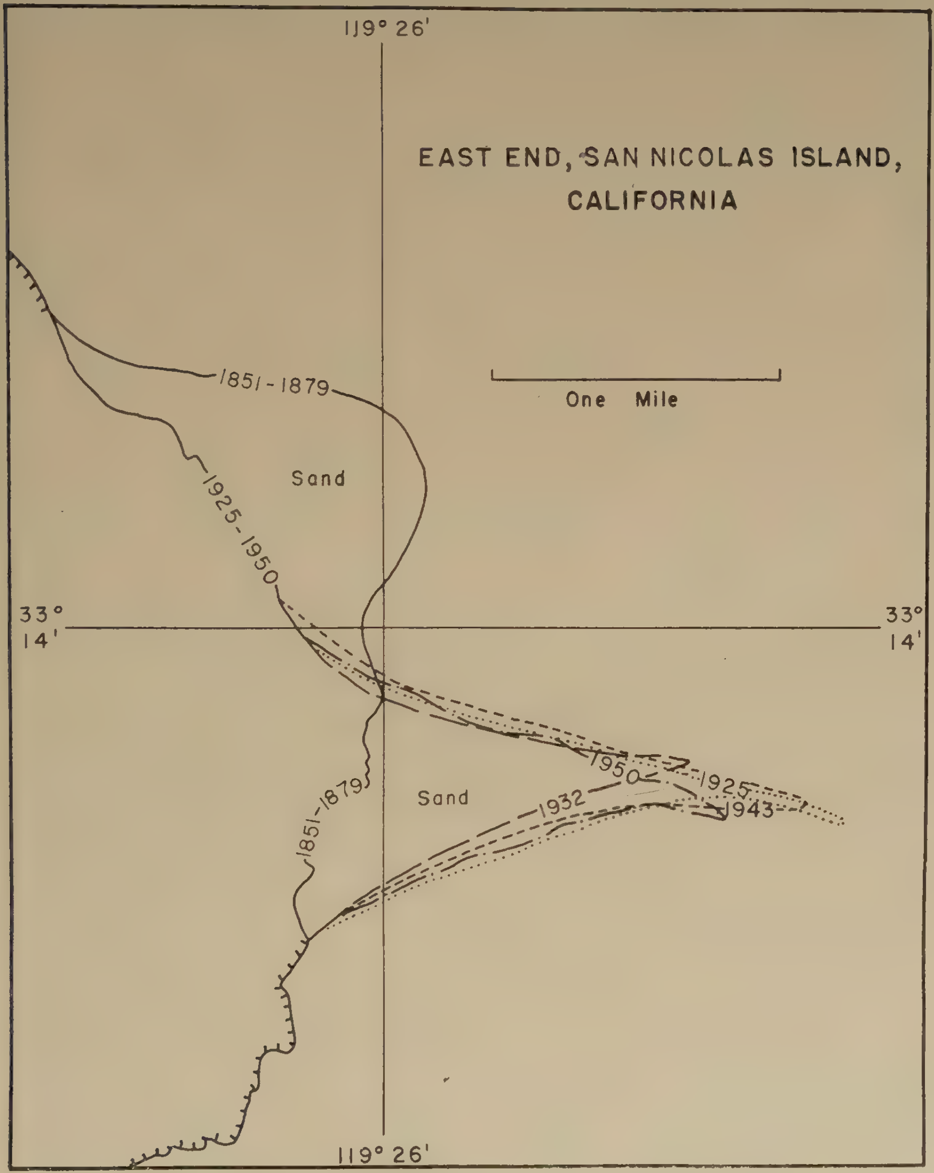
EAST END, SAN NICOLAS ISLAND, CALIFORNIA
119° 26'
One Mile
1851-1879
1925-1950
Sand
33° 14'
33° 14'
1950
1925
1932
1943
1851-1879
Sand
119° 26'

FIG. 3.—Outline map illustrating the changes in the configuration of the sand spit from 1851 to 1950.

coast is less strongly developed and has been observed to move *toward* the island along the south side of the spit.

(3) Sand transported by wind across the top of the island is of minor quantitative importance. Winds blowing across the top of the island carry considerable sand in the western part; dunes and sand hillocks are gradually moving eastward from this area. When winds reach the

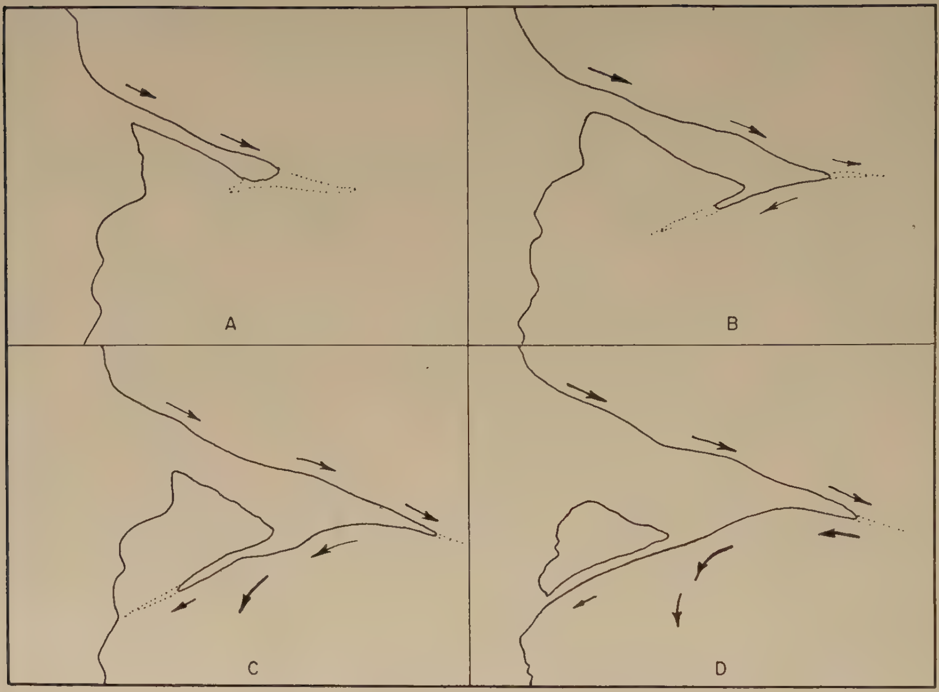

FIG. 4.—Diagram illustrating a possible mode of formation for the San Nicolas sand spit.

eastern end of the island, however, most of their sand load has been dropped, and, owing to the grass cover on the eastern two-thirds of the island, little new load has been acquired.

(4) The position of the spit between 1851 and 1879 shows an even closer relation to the north coast than at present.

CONCLUSIONS

The bulk of material appears to have reached the spit along the northern coast, but the present form has been influenced by the west-flowing current along the south side of the spit. Figure 4 illustrates the development of the present feature as deduced from the currents. The northern side of the spit is a coast of wave deposition and wind erosion, and the outer end of the southern shore is a coast of wave erosion and wind deposition. The inner part of the south side of the spit is most probably a wave deposited bar.

ACKNOWLEDGMENTS

The writer extends his thanks to personnel at the Scripps Institution of Oceanography, La Jolla, California, who have assisted in the field and in the laboratory, especially to Dr. F. P. Shepard who has made helpful suggestions on the manuscript. Valuable criticisms of the manuscript were also made by Dr. R. W. Webb of the University of California at Santa Barbara.

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Heat Flow through the Floor of the Eastern North Pacific Ocean

The flow of heat through the earth's crust has been measured many times at various continental locations, and is usually found to lie[1] within 50 per cent of $1 \cdot 2 \times 10^{-6}$ cal. cm.$^{-2}$ sec.$^{-1}$. Because of the absence of granitic rocks, with their relatively high radioactivity, in the crust under the oceans, it has been suggested that the heat flow through the deep-sea floor might be considerably smaller; but the only data available from oceanic areas have been two measurements of the thermal gradient in deep-sea sediments reported by Pettersson from the Swedish *Albatross* expedition[2].

In 1949, Dr. E. C. Bullard spent the summer at La Jolla in the preliminary development of an instrument for measuring temperature gradients in the sea floor. During the following year, development of instruments of the general type proposed by Dr. Bullard was continued under the direction of J. D. Isaacs and J. M. Snodgrass, and in the summer of 1950 a series of measurements was taken as part of the work of the joint Scripps Institution of Oceanography – United States Navy Electronics Laboratory Mid-Pacific Expedition, on the Scripps research vessel *Horizon*.

A hollow steel spear, 1·64 in. in outside diameter and 10 ft. long, was plunged vertically downward into the bottom sediments and allowed to remain in place for thirty to forty minutes. At its upper end the spear was attached to a heavy steel cylinder containing a self-recording, self-balancing null potentiometer which recorded continuously against time, to about 0·001° C., the difference in temperature between two thermal elements in the spear. The upper element was situated 24·0 in. beneath the sea bottom, and the recording case, and the lower element 81·5 in. beneath the upper element and 18·5 in. from the spear end. The thermal elements were connected thermally to the outside of the spear but were insulated electrically and protected from the outside hydrostatic pressure. We have satisfied ourselves from theory and experiment that the record of temperature difference against time obtained in this way can be extrapolated to give a value which corresponds within a few per cent to the undisturbed temperature gradient in the bottom sediment.

At each locality where the temperature gradient was measured, cores of the sediment were collected

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for laboratory determination of the thermal conductivity; care was taken to preserve these samples in as undisturbed a condition as possible and without change in water content. The conductivity determinations were made by D. W. Butler at the National Physical Laboratory. Because of the high water content of the sediments, the conductivities are much lower than those in rocks and approach the conductivity of sea water ($1 \cdot 3 \times 10^{-3}$ cal. sec.$^{-1}$ cm.$^{-1}$ ° C.$^{-1}$).

The measured temperature gradients and thermal conductivities at six stations and the computed values of the heat flow are given in the accompanying table.

Latitude (North)	Longitude (West)	Depth of water (m.)	Temperature gradient (° C. m.$^{-1}$)	Conductivity (cal. sec.$^{-1}$ cm.$^{-1}$ ° C.$^{-1}$)	Heat flow (cal. cm.$^{-2}$ sec.$^{-1}$)
20° 48′	159° 42′	4,500	0·07	$1 \cdot 8 \times 10^{-3}$	$1 \cdot 3 \times 10^{-6}$
18° 18′	173° 23′	3,900	0·04	$2 \cdot 2 \times 10^{-3}$	$0 \cdot 9 \times 10^{-6}$
19° 28′	174° 35′	4,900	0·06	$2 \cdot 0 \times 10^{-3}$	$1 \cdot 2 \times 10^{-6}$
16° 45′	176° 24′	5,040	0·07	$1 \cdot 8 \times 10^{-3}$	$1 \cdot 3 \times 10^{-6}$
19° 02′	177° 19′	4,750	0·07	$1 \cdot 6 \times 10^{-3}$	$1 \cdot 1 \times 10^{-6}$
32° 35′	132° 30′	4,000	0·07	$1 \cdot 8 \times 10^{-3}$	$1 \cdot 3 \times 10^{-6}$

Although the number of measurements is small, it is noteworthy that at five of the six localities, covering a total distance of nearly three thousand miles, the computed heat flow lies within 10 per cent of the average value for the continents. From field evidence, it is likely that in the observation at long. 173° 23′ W. the spear did not penetrate completely into the sediment, and that consequently the recorded value for the temperature gradient at this locality is too low.

The heat flowing from the deep Pacific floor could represent at least in part a 'fossil' temperature gradient in the sediments, remaining from a time when the bottom-water temperature was higher than the present 1·60°. Short-period temperature fluctuations cannot be significant because observations indicate that deep-water temperatures in the North Pacific have remained constant within a few hundredths of a degree for the past twenty-five years. On the other hand, a markedly different climate five hundred to two thousand years ago might possibly have resulted in somewhat higher bottom-water temperatures in the tropics than those now prevailing. A bottom-water temperature of 4·5° one thousand years ago would account for half the observed gradient.

It might be supposed that the heat flowing from the deep-sea floor has been generated by processes within the sediments, such as biological activity, submarine weathering, radioactivity and compaction. Calculations show, however, that the total effect of these four processes cannot result in production of more than $0 \cdot 05 \times 10^{-6}$ cal. cm.$^{-2}$ sec.$^{-1}$—about 4 per cent of the observed heat flow.

If the heat flowing from the sea floor does not originate within the sediments, it must come from the underlying rocks of the earth's crust and mantle. Seismic refraction measurements made by R. W. Raitt on the Mid-Pacific expedition show that the Mohorovičić discontinuity between the crust and the mantle lies within five to nine kilometres of the sea floor. If the material above this discontinuity is similar in content of radioactive substances to oceanic basalt, then only 15 per cent of the observed heat flow can originate in the crust. If we also assume that the heat is carried from the earth's interior by conduction, and that following Jeffreys[3] the thermal conductivity is 5×10^{-3} cal. cm.$^{-1}$ sec.$^{-1}$ °C.$^{-1}$, only some 20 per cent of the total heat flow can be accounted for by cooling of the earth. The remaining 65 per cent could be supplied by disintegration of radioactive substances in the mantle. But the required content of radioactive materials is so high that, if the radioactivity is uniform with depth or decreases exponentially, the mantle below about 130 km. would melt within a time short compared to 3×10^9 years. It is therefore necessary to assume either that radioactive materials are concentrated in the outer part of the mantle under the ocean, or that the heat is being transported outward by convection in the mantle. If a steady state of convection exists, more than sufficient heat would be generated in a mantle having a uniform potassium content equivalent to that of stony meteorites[4]. In either case, however, we have the paradox that if the mantle under the continents is similar to that under the ocean, then the heat flow from the continents should be much higher than the observed value because of the presence of highly radioactive rocks in the outer parts of the continental crust.

A heat flow of $1 \cdot 2 \times 10^{-6}$ cal. cm.$^{-2}$ sec.$^{-1}$ through the ocean floor should noticeably heat the bottom-water masses as they flow northward from the Antarctic. With a velocity of northward flow of the order of 0·1 cm. per sec., as suggested by Sverdrup, Johnson and Fleming[5], the temperature of a layer of bottom water 1 km. thick would increase by about one-tenth of a degree centigrade on its journey from the region of sinking in the Antarctic to the tropics. This amount of heating would be largely masked by mixing with high-temperature water from above. But with the much smaller velocity of northward flow suggested by some recent workers, there should be a much larger increase in the bottom-water temperature between the Antarctic and low latitudes. Such an increase is not observed. The possibility exists, therefore, that our measurements are not representative of the heat flow through the sea floor. Obviously many more measurements must be taken before reliable generalizations can be made.

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[1] Bullard, E. C., *Nature*, **156**, 35 (1945).

[2] Petterson, H., *Nature*, **164**, 468 (1949).

[3] Jeffreys, H., "The Earth", 85, 2nd edit. (1924).

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THE preceding communication by Revelle and Maxwell gives a result which is completely unexpected, and demonstrates again how little we know of submarine geology. Their observations do, I believe, demonstrate that the heat flow is roughly the same under the oceans and continents. It seems most unlikely that this is a temporary condition dependent on recent large changes in the temperature of the bottom water, for this is largely determined by the existence of ice in the Arctic and Antarctic. The ice cannot have melted since the last ice age, because the water from it would drown the greater part of the continents. It seems almost certain that the heat found by Revelle and Maxwell must be generated by radioactivity in the rocks beneath the oceans, and therefore that the total amount of radioactivity beneath unit area of continent and ocean is the same when summed down to a depth of a few hundred kilometres (heat generated deeper down has not had time to escape). This would be very surprising if the continents were formed from a primitive sialic layer not present under the oceans, and are underlain by material which is the same under continents and oceans. It would, however, be natural if the continents are continuously expanding by a process of differentiation in which radioactive material is concentrated vertically[1]. The rocks beneath the oceans would then have the same total amount of radioactivity as those beneath the continents, but spread through a greater range of depth; this would give the same heat flow as beneath the continents, but higher temperatures at depth.

As is pointed out by Revelle and Maxwell, some upward concentration is necessary to avoid melting under the oceans. Calculation suggests that if the radioactivity were spread through a depth of 150 km., no impossibly high temperatures would be produced. A possible interpretation of the results therefore appears to be that when the earth solidified most of the radioactivity was concentrated in the upper 150 km. of the mantle; under the oceans this distribution still exists, but under the continents a further concentration has occurred into the top 10 or 20 km. On this view it would be expected that the oceanic ultra-basic rocks would contain more radioactive material than the continental ones. There are few reliable measurements; but those that do exist do not show such a difference. This matter should be further investigated.

Other explanations can be suggested. It might, for example, be supposed that at some not too remote time a convection current rose under the Pacific and brought hot material near the surface, or that the horizontal limb of a convection current had transported material from beneath the continents to the central Pacific. Such suggestions are pure speculation, and there is no other evidence in their favour.

The difficulties may be connected with that of reconciling the oceanic seismic and gravity results. The gravity results suggest that the material beneath the Mohorovičić discontinuity may not be quite the same beneath the continents and oceans in spite of the close agreement in seismic velocities. Some discussion of these matters is given in a book[2] to be published shortly.

E. C. BULLARD

National Physical Laboratory,
Teddington.
June 18.

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Actiniaria, Zoantharia and Ceriantharia from Shallow Water in the Northwestern Gulf of Mexico

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INTRODUCTION

This paper is based on long distance collaboration between the authors. Hedgpeth has in the main collected the material and made sketches of the anemones in life and provided notes about the exterior and natural history of the animals. Carlgren has determined the species and in the main prepared the anatomical descriptions and histological drawings.

The collection of anemones from Texas and Louisiana described in this paper consists of material collected from shore and shallow water in Texas by the junior author in the Rockport, Port Aransas and Port Isabel areas, together with material from other localities donated by various collectors. Whenever possible the living material was studied and the nematocysts examined. In all, fifteen identifiable species have been found in the region, thirteen actiniarians, one zoanthid and one ceriantharian, as follows:

Andwakia isabellae n. sp.
Bunodosoma cavernata (Bosc).
Anemonia sargassensis Hargitt
Anthopleura krebsi (Duch. et Mich.)
Bunodactis texaensis n. sp.
Bunodactis sp.
Minyas olivacea (Lesueur)
Paranthus rapiformis (Lesueur)
Calliactis tricolor (Lesueur)
Bartholomea annulata (Lesueur)
Aiptasia pallida (Verrill)
Aiptasiomorpha luciae (Verrill)
Aiptasiomorpha texaensis n. sp.
Botryon tuberculatus n. g., n. sp.
Palythoa texaensis n. sp.
Ceriantheomorphe brasiliensis Carlgren

Although it is possible that more species occur in the shallow waters along the Texas coast, the actinian fauna is evidently poor in comparison with the rich fauna of the Antilles. Louisiana waters are probably even more impoverished, and it is to be noted that only four anemones and a cerianthid have been previously reported from that region (Cary, 1906).

The Corallimorpharia and benthic stichodactyline Actiniaria are completely lacking from the northwestern Gulf of Mexico, as well as representatives of the families Aliciidae and Boloceroididae. Only one species of Zoantharia, which are numerous on the coasts of the West Indies, is found in the waters of Texas. It must be emphasized that these remarks apply to the coastal waters proper; the occurrence of living coral patches on small topographic features near the 100 fathom line suggests that some of the typical West Indian forms may be found on these elevations, some of which rise to within 10 fathoms of the surface. Close inshore, there is but one living madreporarian coral, *Astrangia astreiformis* Milne Edwards and Haime, occurring in small clumps in the deeper parts of the bays near the passes along the Texas coast and in the shallow Gulf. Two alcyonarians, *Renilla mülleri* Kölliker and *Leptogorgia setacea* (Pallas) are common in relatively shallow water in the Gulf along the shore, and a third, *Virgularia mirabilis* (O. F. Müller), occurs occasionally.[1]

The poverty of the actinian fauna in the northwestern Gulf of Mexico can be attributed to several factors. Hard or rocky substrates are lacking, except for the jetties at the passes and the stonework of the bay harbors, pilings, and shell reefs. These offer at best an insignificant opportunity for the development of a rich actinian fauna. Furthermore, the temperature and salinity along the shore, especially near the passes where most of the collecting has been done, and in the bays, is quite variable (see Whitten, Rosene and Hedgpeth, 1950, and Collier and Hedgpeth, 1950); this range of environmental conditions limits the fauna to a few comparatively hardy species.

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[1] We are indebted to Dr. Elisabeth Deichmann for identification of these alcyonarians.

The actinian fauna of the northwestern Gulf of Mexico is predominantly temperate or possibly warm-temperate in its affinities, with a number of tropical strays. Of the thirteen actinians represented in this collection, two occur as far northward as Woods Hole, three northward to Cape Hatteras (one of these has not been found in tropical Florida waters), four are West Indian forms whose northernmost range is Texas or Louisiana, and four species are new, possibly endemic. The remaining species is the ubiquitous *Aiptasiomorpha luciae,* which on the basis of its known distribution can be expected to turn up almost anywhere except the tropics. The characteristic jetty form, found both on the jetties of passes and the harbor works of the bays, *Bunodosoma cavernata,* is a West Indian species ranging as far north as Beaufort, North Carolina. Two species, *Anemonia sargassensis* and *Bartholomea annulata,* are carried to the shore on sargassum, the former as far north as Woods Hole, but these are only accidental guests which do not live long enough to develop new populations. One species, *Minyas olivacea* is pelagic, bearing a float at its aboral end. Among the new and possibly endemic species the most noteworthy is the curious *Botryon tuberculatus.* A small, inconspicuous species, *Aiptasiomorpha texaensis,* is of interest since it appears to be a *bona fide* estuarine species, similar in that respect to *Diadumente schilleriana* of the Ganges Delta region. The occurrence of *Aiptasiomorpha luciae* at Port Aransas during the winter of 1947–48 adds still another locality to the itinerary of this wandering species, which is found at Woods Hole, Beaufort, along the Central California coast, in Japan, the Suez Canal and many other regions. It may not, however, be a naturalized member of the fauna, and its presence in 1948 may have been the sequel to the shipment of a barrel of oysters to Port Aransas from New Jersey for experimental purposes a few months before, or it may have travelled from Delaware to Port Aransas as a fouling organism on the oil tankers which regularly ply between the loading docks at Port Aransas and the refineries at Wilmington. Such circumstances may also account for some of the boreal hydroids on the Texas coast considered by Deevey (1950) as glacial relicts.

Many of the individual anemones are small, an indication, perhaps, of the influence of environmental extremes. According to Coe (1951), the nemerteans of the northern Gulf of Mexico are generally smaller than the northern representatives of the same species. In the case of the actinians, which are for the most part the northernmost representatives of warmer water species, the suggestion that they are smaller representatives of forms which are larger in colder waters cannot apply, and the question of size in relation to temperature is obviously more a matter of the optimum for the species concerned rather than of the temperature conditions *per se.* Picard and Le Roch (1949), have observed a reduction in general size of anemones in waters of reduced salinity along the shore of the northern Mediterranean as compared with those in the sea nearby, and speak of them as "dwarfed forms."

More information is necessary before such a generalization may be safely made about the actinians of the Texas and Louisiana coast; few species are found both in the bays and in the nearby Gulf, and there are too many factors acting upon the life on the jetties along the channel for us to separate these variables without experimentation. One possible example of environmental differences is that presented by *Aiptasia pallida* which occurs offshore near Port Isabel and in South Bay. The South Bay forms appear to be somewhat larger, and are brown, whereas the representatives in the Gulf are very pale blue and generally smaller. In South Bay salinities may be somewhat higher than in the Gulf, but temperatures are also higher, and the food supply is probably greatly different.

KEY TO THE SPECIES

Unfortunately it is not possible to construct a key to anemones which can be used in the field; a few can be determined, in a limited area, on the basis of external characters, but determination of most species requires the examination of prepared sections and of the nematocysts. The latter are best examined in freshly macerated material. The various types of nematocysts to be expected in the species known from Texas and Louisiana are indicated in Figure 1. In the following key, diagnoses are provided for several species which are not completely characterized in the systematic part of this paper.[2]

I. Tentacles in several cycles, the inner cycles larger; *b*-mastigophors and holotrichs lacking or rare; usually with well developed base and contractile column .... ACTINIARIA
   Tentacles arranged in two cycles on the margin, or if in several cycles, the outermost largest .... II.
II. Small polyps without marked pedal disc; solitary or connected by a coenenchyme; column wall usually thick, slightly contractile; with *p* and *b*-mastigophors and holotrichs .... ZOANTHARIA
   Column wall comparatively thin, strongly contractile; column without pedal disc but with a terminal pore; *b*-mastigophors and hoplotelic *b*-mastigophores present, *p*-mastigophors absent; burrowing forms .... CERIANTHARIA

I ACTINIARIA

1. Species with distinct basal disc and basilar muscles 2
   With rounded basal end, without basilar muscles; column divisible into physa, scapus and scapulus; scapus with distinct tenaculi; sphincter mesogleal; 2 siphonoglyphs and 2 pairs of directives; 24 pairs of mesenteries, 6 of which are perfect; retractors strong on the perfect mesenteries, restricted to circumscribed on others and lacking pennons; acontia on at least some of the mesenteries .... *Andwakia isabellae*
2. Species without acontia 3
   Acontia present 8
3. With marginal spherules, usually containing atrichs, rarely lacking; lower part of the column often with atrichs 4
   Without marginal spherules 6
4. Column with rows on non-adhesive vesicles or adhesive verrucae 5
   Column smooth, low; sphincter diffuse, not strong; tentacles variable in number, up to 40–50, often irregularly arranged; 2 or no siphonoglyphs; 2 directives or none; arrangement of the mesenteries often irregular as a result of asexual reproduction, or regular; retractors of the mesenteries diffuse .... *Anemonia sargassensis*

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[2] For descriptions of the anatomy of sea anemones, see Hyman, L., The Invertebrates, Vol. I, Protozoa through Ctenophora (McGraw Hill, 1940), p. 566 ff., and Stephenson, T. A., The British Sea Anemones (Ray Society, 1928), Vol. I.

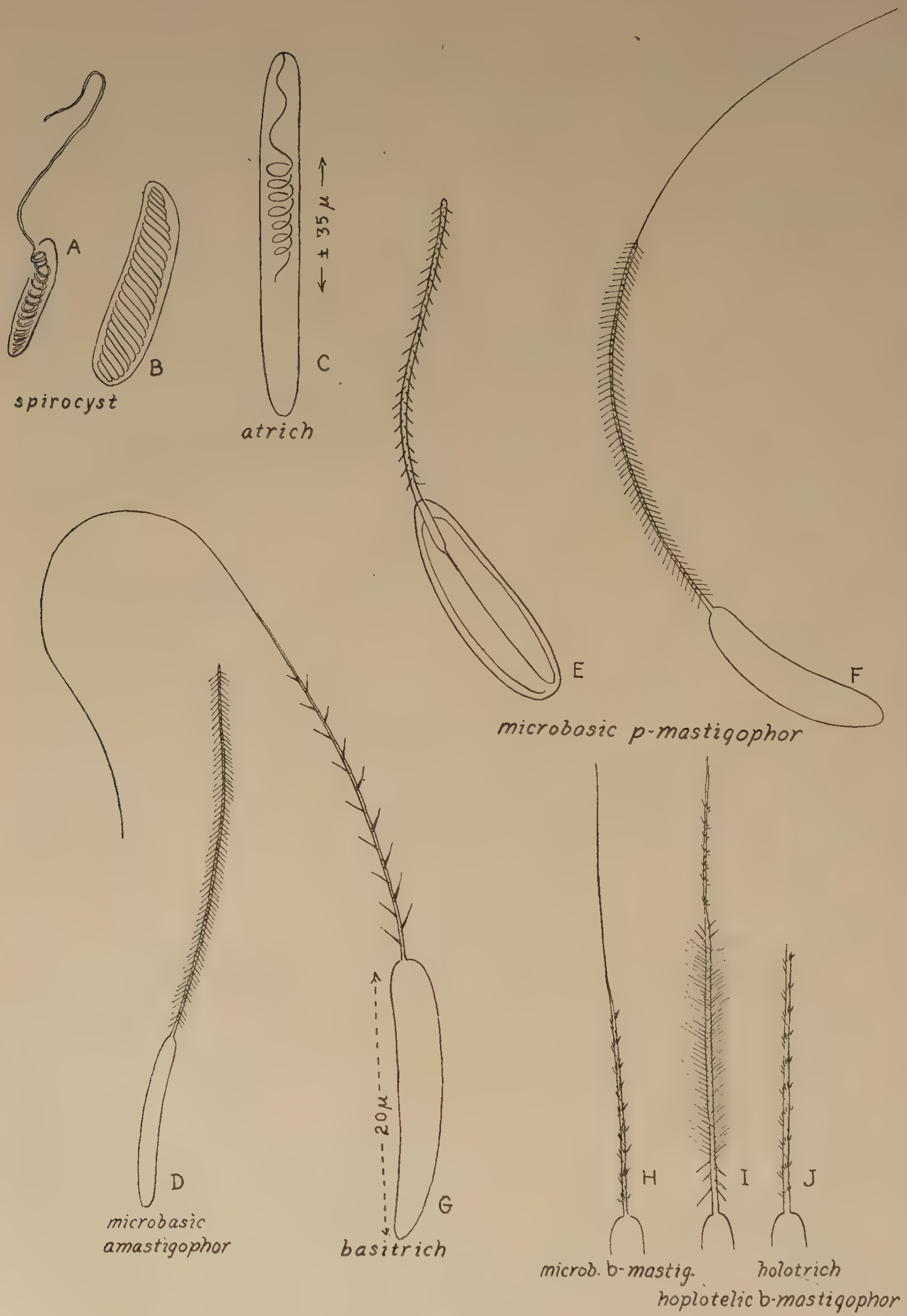
A
B
spirocyst
± 35 μ
C
atrich
E
F
microbasic p-mastigophor
D
microbasic
amastigophor
20μ
G
basitrich
H
I
J
microb. b-mastig.
holotrich
hoplotelic b-mastigophor

FIGURE 1

Types of nematocysts found in the species described in this paper: A, B, spirocysts, ruptured and unexploded, from *Paranthus rapiformis.* C, partly unexploded atrich, from *Ceriantheomorphe brasiliensis* (After Carlgren, 1940). D, microbasic amastigophor, from *Aiptasia pallida.* E, F, microbasic *p*-mastigophor, *Aiptasiomorpha luciae*, partially and completely exploded. G, basitrich, from *Bunodactis texaensis.* H, microbasic b-mastigophor; I, hoplotelic b-mastigophor. J, holotrich (H, I, J, diagrammatic).

5. Entire column provided with rows of (non-adhesive) vesicles; sphincter circumscribed, strong; tentacles rather short, up to 96; 2 distinct siphonoglyphs and 2 pairs of directives; most of the mesenteries perfect and fertile .... *Bunodosoma cavernata*

Column provided with rows of adhesive verrucae; sphincter circumscribed, weak; tentacles rather short, not numerous; arrangement of the mesenteries irregular, owing to longitudinal fission .... *Anthopleura krebsi*

6. Without adhesive verrucae on the column 7

Column with rows of adhesive verrucae; sphincter circumscribed; tentacles cyclically arranged, up to 96 in number; 2 siphonoglyphs and 2 pairs of directives; 24 pairs of perfect mesenteries; all stronger mesenteries fertile .... *Bunodactis texaensis*

7. Body melon shaped, with 20 longitudinal furrows; pedal disc invaginated, so that an opening is visible in the aboral end, the cavity of the aboral end containing a structure forming a hydrostatic apparatus; sphincter circumscribed, very weak; tentacles papilliform, arranged in radial series; one spihonoglyph and two pairs of directives; arrangement of the mesenteries different from the common scheme because of an enlargement of the endocoels and reduction of the exocoels, giving the appearance of many directive pairs; retractors strong .... *Minyas olivacea*

Body elongate, smooth; sphincter mesogleal; tentacles rather short, more numerous than the mesenteries at the base; 2 siphonoglyphs, 2 pairs of directives; at least 12 cycles of mesenteries perfect in fertile specimens; retractors of the mesenteries strong .... *Paranthus rapiformis*

8. Acontia bearing two types of nematocysts 9

Acontia bearing only basitrichs; column with an annulus of cinclides near the base; sphincter strong, mesogleal; tentacles up to 96 in number; 2 siphonoglyphs and 2 pairs directives; 6 pairs of perfect and fertile mesenteries; retractors weak, diffuse .... *Calliactis tricolor*

9. Acontia with microbasic *p*-mastigophors and basitrichs; cinclides present 10

Acontia with microbasic amastigophors (?) and basitrichs; cinclides absent; at least 12 pairs of perfect mesenteries; column with longitudinal rows of mesogleal papillae more or less regularly arranged; all or almost all mesenteries fertile, the male organs (at least) forming botryoid clusters .... *Botryon tuberculatus*

10. With mesogleal sphincter; column smooth, regular, not divisible into scapus and capitulum 11

Without sphincter; column divisible—or apparently so—into scapus and capitulum 12

11. Sphincter rather well developed; tentacles long, not retractile, smooth, up to 96 in number; 6 pairs of perfect mesenteries; 2 siphonoglyphs and 2 pairs of directives; retractors of the perfect mesenteries diffuse or restricted; cinclides in middle part of the column; reproduction by laceration (constriction) .... *Aiptasia pallida*

Sphincter not strong; tentacles long, not retractile, considerably more than 96 in full grown individuals, bearing raised bands of nematocyst batteries; 6–8 pairs of perfect mesenteries .... *Bartholomea annulata*

12. Column divisible into scapus and capitulum, the former ending in a very distinct parapet; cinclides present from parapet to base; tentacles long, irregularly arranged; number of siphonoglyphs and directive mesenteries as well as perfect mesenteries variable owing to reproduction by longitudinal fission .... *Aiptasiomorpha luciae*

Column apparently divisible into scapus and capitulum; cinclides in a ring in the middle of the column; sphincter apparently absent; tentacles long, few, probably not retractile; 2 siphonoglyphs and 2 pairs of directives; 6 pairs of perfect and fertile mesenteries; reproduction probably by laceration .... *Aiptasiomorpha texaensis*

II. ZOANTHARIA

Free polyps; column incrusted with grains of sand occupying the whole mesoglea; divisible into scapus and scapulus, the scapular ridges distinct; sphincter mesogleal; tentacles 28, arranged in two cycles; one siphonoglyph; 28 mesenteries .... *Palythoa texaensis*

III. CERIANTHARIA

Column cylindrical, its aboral end rounded, with a strong longitudinal muscle layer; tentacles in several cycles, partly at the margin, partly at the mouth; one siphonoglyph and one pair of directives; directive mesenteries rather short, also the third protomesenteries; second protomesenteries long, reaching almost to the aboral end, provided with craspedonemes on the orthocraspedon (ciliated streaks), in almost their whole length, and a small plectocraspedon (cnidoglandular streak) in their aboral end; older metamesenteries 1 and 3 (M and m) in each quartette somewhat longer than the directives, with craspedonemes forming a bunch in the lowest part close to the plectocraspedon; matamesenteries 2 and 4 (B and b) shorter than the directives, their orthocraspedon often with craspedonemes, but not forming the clusters at the plectocraspedon; all mesenteries, except the directives, fertile .... *Ceriantheomorphe brasiliensis*

SYSTEMATIC DISCUSSION

ORDER ACTINIARIA

Family ANDWAKIIDAE

Andwakia isabellae n. sp.

Figure 2, A-E

Material examined: Off Port Aransas, Texas, May 18, 1933. K. H. Mosher, coll., 1 specimen (no other data) (Paratype, U.S.N.M. No. 49981). Off Port Isabel, in about ten fathoms, sandy bottom, with try net, March 30, 1947, J. Hedgpeth, coll., 1 specimen (Holotype, U. C. N. M. No. 49982).[3]

Description: The base is apparently rounded, but from the available material it is not possible to be certain that basilar muscles are absent, although they appear to be lacking. The column is divisible into scapus and scapulus, the former provided with numerous well developed tenaculi. The sphincter is mesogleal, reticular, occupying a part of the mesoglea, but owing to the inadequate material cannot be adequately figured. The tentacles are arranged in 4 cycles, thus 48 in numbers (observation by Hedgpeth). They are very small in comparison to the size of the animals and their longitudinal muscles ectodermal, palisade-like in arrangement. There are two well developed siphonoglyphs. The pairs of mesenteries are $6 + 6 + 12 = 24$; two pairs are directives and six pairs are perfect. The retractors of the perfect mesenteries are very strong, strongly restricted to circumscribed in cross section (Fig. 2, C and E), the longitudinal muscles of the other mesenteries form no pennons, but are rather well developed (Fig. 2, D). The parietal muscles of the perfect mesenteries resemble the muscles of the imperfect mesenteries. All mesenteries are provided with filaments and at least a part of them with acontia. Owing to the smallness of the other mesenteries, it is probable that only the perfect mesenteries bear generative organs. The nematocysts of the scapulus are microbasic *p*-mastigophors or amastigophors, often curved, 19.7–24 (26.8) x 4.2–5.6 μ; those of the tentacles, basitrichs, 21–28.2 x 2.8 μ; those of the actinopharynx partly basitrichs, 24.7–32.4 x 2.8 μ (25.4–31 x 2.5–3 μ): partly amastigophors (probably), 25.9–33.8 x 5.6–7 (8.5) μ, (28.2–33.8 x 5.6–7 μ); of the filaments partly basitrichs, 8.5–15.5 x 1.5–2.2 μ (12.7–15.5 x 2 μ), partly microbasic *p*-mastigophors (13.4–17 x 3.5–4.5 μ); of the acontia partly basitrichs, 15.5–21 x2.2–2.5 μ, partly microbasic amastigophors or *p*-mastigophors, 42.3–48 x 8.5–10μ. (The measurements in parentheses are from the specimen from Port Isabel.)

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[3] "Material examined" indicates the material sent to Sweden to be examined by the senior author; in some cases, as indicated in the text, more material was collected.

The specimen from Port Isabel (expanded) is 8.5 cm. long, the largest diameter 2.5 cm., the tentacles 1 cm. long; the contracted specimen from Port Aransas is 7 cm. by 3.2 cm.

Color: Oral disc gray, with darker zigzag markings, darker markings at the base of the tentacles and on the tentacles (see Figure 2, B).

Remarks: Unfortunately both samples as sent to Sweden were previously dissected, and owing to the poor condition of the basal part it is difficult to decide whether the specimens belong to *Andwakia* or *Epiphellia*, but as the basilar muscles are apparently absent the specimens may at present be referred to *Andwakia*.

Family ACTINIIDAE

Bunodosoma cavernata (Bosc)

Plate I; Figure 2, F–H.

Bunodes cavernata Bosc, 1802, p. 22.

Actinia granulifera Lesueur, 1817, p. 173.

Phymactis cavernata Andres, 1883, p. 448; Field, 1949, p. 10.

Bundosoma granulifera Duerden, 1902, p. 348; Pax, 1910, p. 184; Carlgren, 1949, p. 51.

Bunodosoma cavernata Carlgren. 1949, p. 51; Whitten, Rosene and Hedgpeth, 1950, p. 94.

Material examined: Port Aransas, Texas, rocks near jetty at low tide 3 specimens; Port Isabel, Texas, 2 specimens (One, very large), from ship channel, sandy-muddy bottom, about 25 feet. March 15, J. W. Hedgpeth, coll.

Description: The pedal disc is well developed. The entire column is provided with very close set vesicles. At the margin there is an annulus of spherules (rarely absent. as in the young specimen from Port Isabel). The sphincter is circumscribed, agreeing well with the sphincter of *granulifera* figured by McMurrich (1889, Pl. III, fig. 7) and Duerden (1902, Pl. IX, fig. 34). In the large specimen it is of the same type but broader, and the muscle lamellae are very numerous (Figure 2, F). The tentacles are rather short and up to about 96 in number. There are two siphonoglyphs and two pairs of directives. The retractors are band-like and the parietobasilar muscles well developed. The nematocysts of the lower part of the column, the marginal spherules and the tentacles in the three small examples from Port Aransas and of the other organs in one specimen from the same locality have been examined. The nematocysts of the lower part of the column are partly basitrichs, 12.7–21 x 2.2–8 μ, partly atrichs, 18.3–22.6 x 4–4.5 μ; of the marginal spherules, atrichs, 33.8–46.5 x 4.2–5μ; of the tentacles, basitrichs 15.5–19.7 x 2.2–2.8 (3 specimens examined); of the actinopharynx, partly microbasic *p*-mastigophors, 17–19 x ca. 4.2 μ, basitrichs, partly 12–22.6 x 2.2–3 μ: of the filaments, partly microbasic *p*-mastigophors, 18.3–20.4 x 4.5 μ, partly basitrichs, 24–35.2 x 4.5–6.3 and 12.7–15.5 x 2.2–3 μ.

In the very large specimen from Port Isabel the nematocysts of the lower part of the column and tentacles are larger, in the column, partly basitrichs (sparse), 18.3–

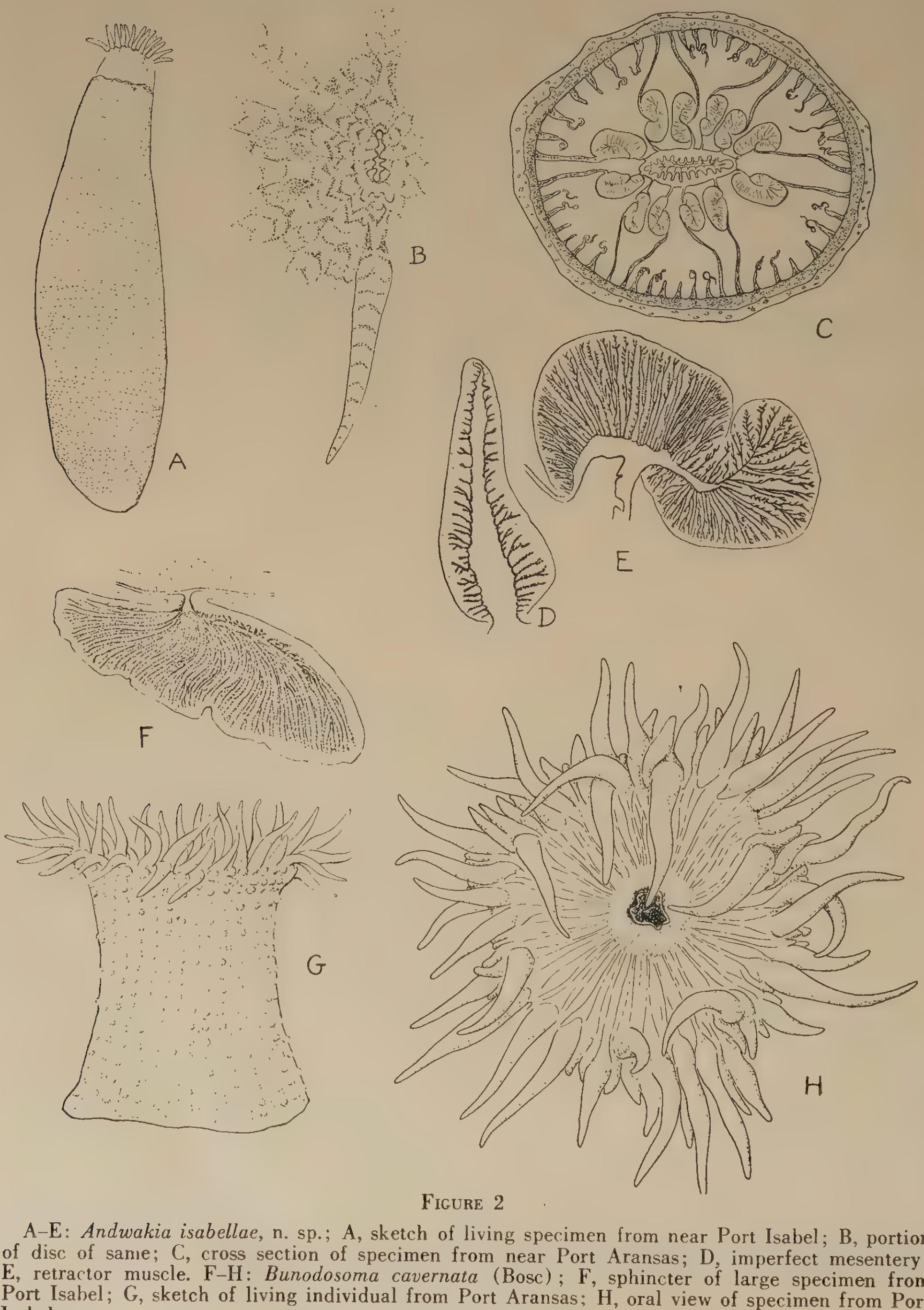

FIGURE 2

A–E: *Andwakia isabellae*, n. sp.; A, sketch of living specimen from near Port Isabel; B, portion of disc of same; C, cross section of specimen from near Port Aransas; D, imperfect mesentery; E, retractor muscle. F–H: *Bunodosoma cavernata* (Bosc); F, sphincter of large specimen from Port Isabel; G, sketch of living individual from Port Aransas; H, oral view of specimen from Port Isabel.

25.2 x 2.8–3 μ, partly larger basitrichs?, probably atrichs (very rare), 31–36 x 4.2–6.5 μ; in the marginal spherules atrichs, 31-42.3 x 3.5–5 μ; in the tentacles basitrichs, 18.3–26.8 x 2.8 μ; in the actinopharynx partly microbasic *p*-mastigophors, 21–24 x 5.5 μ, partly basitrichs of probably two sorts, 14–28.2 x 2.5–4.2 μ, in the filaments partly microbasic *p*-mastigophors, 18.3–24 x 4.2–6.3 μ, partly basitrichs, 21–42.3 x 3–7 μ (also smaller basitrichs, not measured). It might appear that we are dealing with two different species, but this is probably not the case. In two specimens of medium size from Beaufort the basitrichs in the lower part of the column and in the tentacles are up to 24–25.4 μ long, although the largest ones are sparse. Evidently the basitrichs may be larger with the increasing age of the species. The number of atrichs in the lower part of the body varies considerably, from very numerous to very rare.

Color: Light brown with bluish vesicles, tentacles and oral disc from deep red and blue to pale olive-brown. The color of Texas jetty specimens agrees well with notes provided by T. A. Stephenson for *B. cavernata* at Beaufort: "There are sometimes more or less definite blue shades on the oral faces of the tentacles especially on the outer ones and the aboral sides of the tentacles may be red." A sample from Port Isabel had the column olive-green, the oral disc yellowish olive-green and the marginal spherules dull tan-green. Another sample, the largest, from the bottom of a muddy-sandy channel, was entirely muddy-brown. Other specimens, from the Port Isabel jetties show agreement with those of *granulifera* described by Duerden, a vaguely striped appearance of the column, the dull cream or yellowish tentacles and a scarlet rim around the mouth. Evidently the color of the species varies considerably.

Remarks: From the agreement of the color and of the sphincter, etc., it is apparent that *cavernata* and *granulifera* are the same species. Some variations of the sphincter are discussed in another paper (Carlgren, 1952, p. 2).

Distribution: Bahamas, Puerto Rico, Jamaica, Barbados, Guadeloupe, Martinique, St. Thomas, Curaçao, in the West Indies; on the Atlantic coast from north Florida to Cape Hatteras; on the northwestern Gulf Coast at Port Isabel, Port Aransas, Rockport, Texas and Cameron, Louisiana.

Anemonia sargassensis Hargitt

Plate IV; Figure 3, A-D.

Anemonia sargassensis Hargitt, 1908, p. 117; 1914, p. 239, Pl. LI, fig. 3, Pl. XLIV, fig. 3; Field, 1949, p. 9, Pl. IV, figs. 38–41, Pl. V, figs. 42–46.

Material examined: From sargassum, St. Joseph Island, Texas, April 8, 1946, several specimens. J. W. Hedgpeth, coll.

The anatomy of this species is described by Field (1949) but there are several details which may be corrected and completed at this time.[4] The pedal disc is well developed, the body, at least in contracted state, low, short. The column is smooth, at the margin provided with spherules "protuberances from the periphery of the oral [!] disc"—Field), which, however, are rather weak. The sphincter is diffuse, not strong (Fig. 3, D). The tentacles are rough, the inner considerably stronger than the small outer ones, but as the arrangement is irregular, small tentacles occurring between the larger, their number is up to 40–50. The longitudinal muscles of the tentacles and the radial muscles or the oral disc are ectodermal. The siphonoglyphs, if present, are weak. Unfortunately the actinopharynx of two sectioned specimens is very folded, so that it is difficult to make out the number of the siphonoglyphs, but there are several furrows with somewhat stronger cilia, possibly indicating the presence of siphonoglyphs. Field has indicated (in figure 38) two siphonoglyphs, but as the sections were taken in the region of the tentacles it is very doubtful that there were any siphonoglyphs in her specimen. Hargitt figures, however, a young specimen with two siphonoglyphs and two pairs of directives. Neither in Field's nor our specimens were directive mesenteries present. Evidently the species propagates asexually, probably by longitudinal fission. Two examined specimens had 9 and 12½ pairs of perfect mesenteries respectively. Field says that there are 24 perfect pairs at the oral end of the actinopharynx; her figure 38 shows, however, apparently 11 pairs of perfect mesenteries. The retractors are diffuse (Figure 3, D). No gonads are developed in the two sectioned samples. There are considerably more mesenteries at the base than at the margin. The nematocysts of the column are basitrichs, 15.5–19.7 x 2.2–2.8 μ; those of the marginal spherules partly atrichs, 33.8–39.5 x 5–6.3 μ, partly basitrichs, 15.5–21.1 x 2.2–2.8 μ; those of the tentacles basitrichs, probably of two sorts, 15.5–33.8 x 2.2–3 μ; those of the actinopharynx partly basitrichs of two sizes, 19.7–25.4 x 3.5–4.6 μ, 15.5–28.2 x 2.2–2.8 μ, partly microbasic *p*-mastigophors, 18.3–19.7 x 5–5.6 μ; those of the filaments partly basitrichs, 21–36.7 x 4.2–5.6 μ and 15.5–28.2 x 2.5–2.8 μ, partly microbasic *p*-mastigophors, 18.3–22.6 x (4.2) 5.6–6.3 μ.

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[4] For further comments on the paper by Field, see T. A. and Anne Stephenson, 1952, pp. 34–35, and Carlgren, 1952, p. 16.

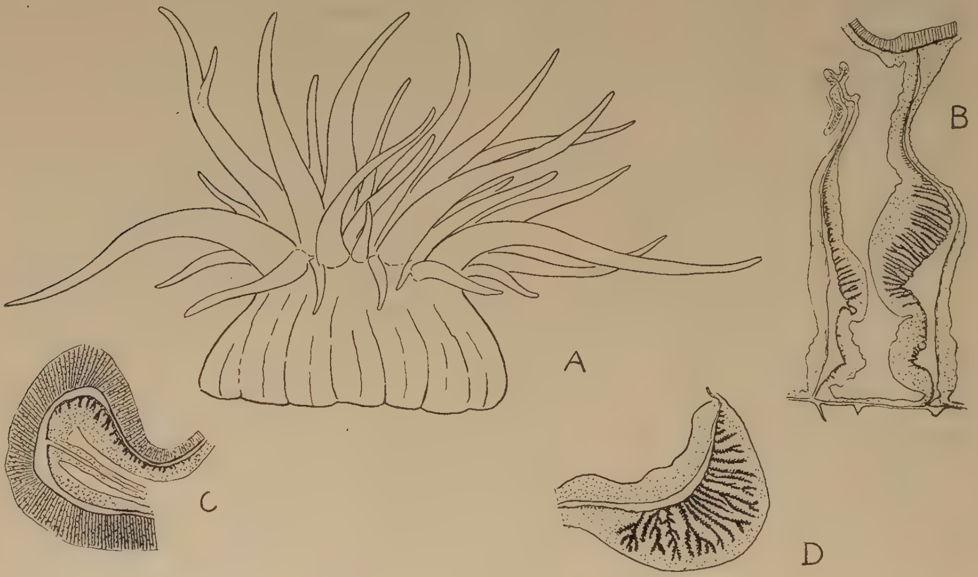

FIGURE 3

Anemonia sargassensis Hargitt: A, sketch of living individual; B, transverse section through two mesenteries; C, sphincter; D, retractor from perfect mesentery.

In the preserved state the largest specimen examined had a pedal disc (somewhat contracted) about 0.5 cm. in diameter, that of the column below the tentacles 0.7 cm. The length of the largest tentacles was about 0.8 cm.

Color: Brown with cream colored sectors on disc, a brown annulus around the mouth. Some samples are paler, with tentacles pale green at the tips (See also Hargitt and Field).

Distribution: Woods Hole, Massachusetts; Beaufort, North Carolina; Port Aransas, Texas.

Remarks: It has been pointed out to us by M. D. Burkenroad that there may be two anemones regularly inhabiting eupelagic *Sargassum*, a somewhat larger, darker form, fairly common in the Gulf of Mexico, but not in the Atlantic, and a smaller, light-colored form common in both Atlantic and Gulf. It is therefore not entirely certain whether the anemone described by Hargitt is the same as the *Actinia pelagica* of Quoy and Gaimard (*Voyage de l'Astrolabe*, Zool., vol. 4, p. 146, pl. 11, fig. 10). Milne Edwards and Haime (1857), vol. 1, p. 235), cited *pelagica* as a species of *Anemonia*, and it is not clear why their color description, based apparently on Quoy and Gaimard, was thought by Hargitt to be inapplicable to his specimens. Certainly Hargitt's belief that "compared with *A. sargassensis* [*A. pelagica*] has many points of difference, such as color, number of tentacles, etc." seems a poor basis for discarding Quoy and Gaimard's name. Hargitt's color figure, incidentally, appears to be out of scale as related to the sprig of sargassum, i.e., it is about twice as large as the dimensions indicated in the text. The color shown corresponds to that of the small, pale form, which may not reach the dimensions given in Hargitt's text. Adequate descriptions or determinations of anemones from mid-Atlantic *Sargassum* are not available in the literature; Timmermann (1932), for example, simply refers to "actinians," and in most accounts of the sargassum fauna they are not mentioned at all. If there is a single, variable species of anemone regularly inhabiting eupelagic *Sargassum*, there would be little doubt that Hargitt's species is a synonym of *A. pelagica* (Quoy and Gaimard). If there are two such species in the Gulf, the question whether Hargitt's name might refer to a different one than Quoy and Gaimard's remains open. Our description and illustrations apply to the larger, dark form, and probably to the species examined by Field at Beaufort.

Anthopleura krebsi Duch. et Mich.

Plate I; Figure 4, A–D.

Anthopleura krebsi Duchassaing and Michelotti, 1860, p. 49, Pl. VII, fig. 3; 1866, p. 126; Andres, 1883, p. 440; Whitten, Rosene and Hedgpeth, 1950, p. 74.

Bunodes krebsi Duerden, 1898, p. 454.

Material examined: North jetty, Brazos Santiago Pass, Texas; on small rocks at base of jetty, low tide, May 5, 1946; 2 specimens. J. W. Hedgpeth, coll.

Both specimens are young, and a detailed description cannot be given. The base is well developed. The column is provided with vertical rows of simple warts on its entire length, very indistinct on the preserved, extended specimens, but conspicuous in the living animal. The largest verrucae occur on the upper part of the column. Marginal spherules are present. The tentacles are few in these specimens. The sphincter is circumscribed, weak, probably because of the small size of the specimens (Fig. 4, B). As the species has been observed to divide by longitudinal fission (J. W. H.), the arrangement of the mesenteries is probably irregular. The retractors of the older mesenteries are rather well developed and more or less restricted; the parietobasilar muscles form a distinct fold on the mesenteries. The specimens are not fertile. The nematocysts of the column are partly basitrichs, 17–19.7 x 2.5–2.8 μ, partly atrichs (probably; they are opaque), 16.5–19.7 x 4.2–4.5 μ; those of the marginal spherules partly atrichs, 32.4–43.7 x 4.5–5 μ, partly basitrichs, 12.7–15.5 x 2.2–2.8 μ; those of

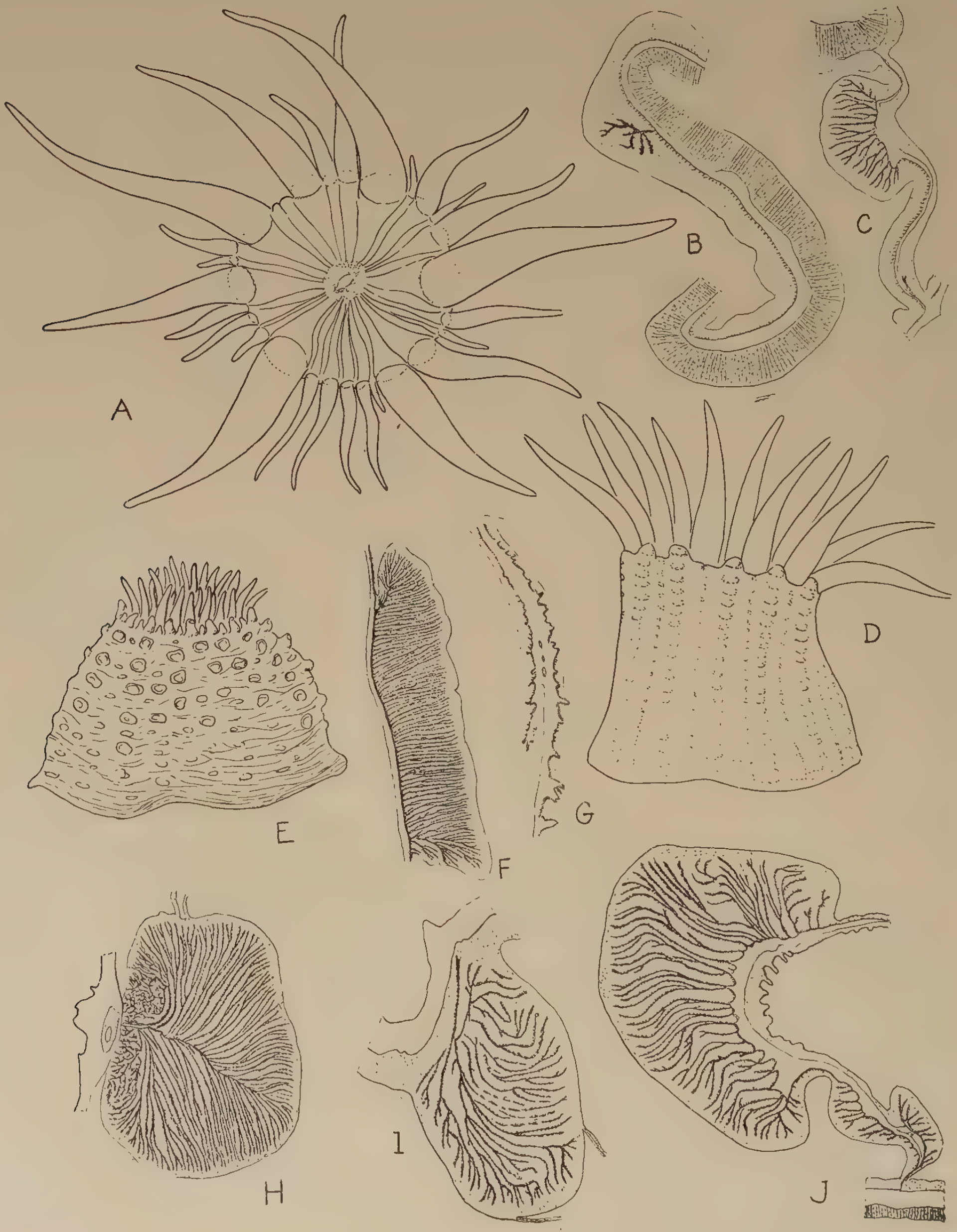

FIGURE 4

A–D: *Anthopleura krebsi* (Duch. et Mich.); A, oral view; B, sphincter; C, perfect mesentery; D, side view, E–H: *Bunodactis texaensis* n. sp.; E, view of partly contracted specimen; F, parieto-basilar muscle; G, retractor; H, sphincter. I–J; *Bunodactis* sp.; I, sphincter; J, section of perfect mesentery below the actinopharynx.

the tentacles basitrichs (very numerous), 15.5–18.3 x 1.5–2.5 μ; those of the actinopharynx partly basitrichs, 21–25.4 x 3–3.5 μ, partly microbasic *p*-mastigophors, 19.7–21 x ca. 5 μ; those of the filaments basitrichs, partly 18.3–28.2 x 4.2–5.6 μ, partly microbasic *p*-mastigophors, 17–19.7 x 5–5.6 μ.

The largest specimen is about 1 cm. long by 0.5 cm. broad. According to Duerden the length is 2.5 cm., the disc 2.3 cm. and the inner tentacles 1.2 cm. long. Evidently the species is always small.

Color: Column pale pink with light red warts in regular rows, tentacles white or transparent grayish lavender (See also Duchassaing and Michelotti, and Duerden).

Distribution: St. Thomas, Jamaica, south Texas.

Bunodactis texaensis, n. sp.

Plate I; Figure 4, E–H.

Material examined: Galveston, April 24, 1939. O. Sanders, coll. 1 specimen (Holotype, U.S.N.M. No. 49988); near Bell Buoy, Port Aransas, Texas, 10 fathoms, mud, Oct. 22, 1946, J. W. Hedgpeth, coll. 1 specimen.

Description: The pedal disc is broad. The whole column is provided with simple verrucae, larger in the upper part than in the lower. At the margin there is a ring of pseudospherules. The sphincter is strong, circumscribed with a thin, sometimes rather indistinct main lamella (Fig. 4, H). The tentacles are rather short, about 96, and hexamerously arranged. Their longitudinal muscles are ectodermal and palisade-like in arrangement. There are two siphonoglyphs, symmetrically set. The pairs of mesenteries are about 48, with two pairs of directives and 24 perfect mesenteries. The retractors of the 24 stronger pairs are band like (Fig. 4, G), the parietobasilar muscles are strong, forming a distinct fold on the mesenteries (Fig. 4, F). All the stronger mesenteries are fertile, including the directives. There are the same number of mesenteries at the margin as the base in the specimen from Port Aransas. The nematocysts of the column are basitrichs, 8.5–15.5 x 1.5–2 μ (12.7–17 x 2.2–2.5 μ); of the pseudospherules basitrichs, 10–12.7 x 1.5–2 μ (11.3–14 x 1.5 μ); those of the tentacles basitrichs, 17–21 x 2.5–2.8 μ (12.7–18.3 x 2.2–2.5 μ); of the actinopharynx partly basitrichs, 19–25.4 x 3 μ (21–26 x 3–3.5 μ), partly microbasic *p*-mastigophors, 17-19.7 x ca. 4.2 μ (16.2-18.3 x 4.2–5.6 μ), partly basitrichs, 22.6–38.4 x 3.5–5.6 μ (32.4–39.5 x 4.2–5.6 μ). The sizes in parentheses are of the nematocysts from the Galveston specimen, the other measurements are from the Port Aransas specimen.

The strongly contracted specimen is about 2.8 cm. in length and diameter; the other specimen is smaller.

Color: (Of the Port Aransas specimen) Column a uniform, translucent gray, tentacles gray with darker gray streaks, and pale to white annular patches on the first three cycles. Oral disc a pale brownish green with dark gray splotches and regular markings as indicated (Plate I). In formalin there is a greenish longitudinal band on each side of the tentacles.

Remarks: The decription above is based principally on the specimen from Galveston, because the specimen from Port Aransas has now been mislaid (O. C.); there is however no doubt that both are the same species.

Bunodactis? sp.

Figure 4, I–J.

Material examined: Bell Buoy, Port Aransas, Texas, Oct. 22, 1946, 1 specimen. J. W. Hedgpeth coll.; Jetty, Brazos Santiago Pass, March 20, 1947, 1 specimen. J. W. Hedgpeth coll.

These two immature specimens, collected from different localities are apparently identical species, and possibly are young *Bunodactus texaensis* (the sizes of the nematocysts agree rather well), or young *Anthopleura.* The young stages are very difficult to separate in these two genera. These genera are principally separated on the basis of the presence of marginal spherules (containing atrichs) in *Anthopleura* and their absence in *Bunodactis,* but in young *Anthopleura,* the marginal spherules are not developed. Therefore there is the possibility that these two specimens may be Anthopleuras. The column is cylindrical, provided with longitudinal rows of verrucae, which in the younger specimens from Santiago Pass are few, and present only in about the upper half of the body, and in the specimen from Port Aransas are indistinct on the lower part of the column. At the margin there is a ring of pseudospherules. In the larger specimen a rather well developed circumscribed sphincter is present (Fig. 4, I), in the smaller one it is apparently absent. It is, however. not impossible that the latter could have developed a circumscribed sphincter, as we know that the sphincter can be very weak in larger specimens than this one (Cf. *Bunodactis krebsi* and *Minyas (Stichophora) torpedo* (Haddon 1898)). Furthermore, too little is known about the time of development of the sphincter in a species. The tentacles are few in the smaller specimen, 44 in the larger one. There are two distinct siphonoglyphs and two pairs of directives. Twelve pairs of mesenteries, among them 6 pairs of primaries and at least a part of the second cycle, are perfect. The retractors are strong and band like, in the directives more restricted and kidney-like, or more restricted (Fig. 4, J). The parietobasilar muscle is strong and forms a distinct fold on the mesenteries (Fig. 4, J). Both specimens are sterile. The nematocysts of the lower part of the column are partly basitrichs, 12.7–15 x 2.5 (11.5–17 x 1.5–2 μ), partly opaque, indeterminable, 14–15.5 x 3–3.5 μ; of the marginal pseudospherules, very numerous basitrichs, 10.6–13.4 x 2.2 μ (10–14 x 1.5 μ); of the tentacles, basitrichs, 17–21 x 2.5 μ (14–21 x 1.5–2 μ); of the actinopharynx partly basitrichs, 18.3–24 x 2.8–3.5 μ (19.7–22.6 x 2.5–2.8 μ), partly microbasic *p*-mastigophors, 17–18.3 x 4.2 μ; of the filaments partly basitrichs, 22.6–33.8 x 3.5–6 μ (24–32.4 x 4.2– 5.6 μ), and 10–55.5 x 1.5–2 μ (10–14 x 1.5 μ), and microbasic *p*-mastigophors, 16.2–19 x 4.2 μ (17–19 x 4.5–5 μ). The nematocysts in parentheses are from the smaller specimen.

Size in preserved condition, of the Port Aransas specimen: length 1.5 cm., diameter, ca 0.9 cm. Of the specimen from Brazos Santiago: length, 0.7 cm. (in life, 1.2 cm.); diameter 0.2 cm., length of the tentacles about 0.3 cm.

Color: (Brazos Santiago specimen) Transparent, colorless.

Family MINYADIDAE

Minyas olivacea (Lesueur)

Figure 5, A–C.

Minyas olivacea Andres, 1833 (synonyms and literature), p. 556; Carlgren, 1894; Carlgren 1924, p. 66.

Material examined: "Front Beach," Grand Isle, Louisiana. E. H. Behre, leg. 1 specimen (of two collected).

Description: The body is melon-shaped with 20 longitudinal furrows indicating 20 pairs of mesenteries. Papillae as figured by Lesueur were not seen by Carlgren, but as they seem very small in the type, they may have disappeared in the young and preserved specimen. In the other, slightly larger specimen, there is a suggestion of such structures (J. W. H.). At the aboral end there is an opening to a cavity containing the proteinaceous(?) structure which functions as a float, as in other Minyadidae. The sphincter is endodermal. circumscribed, but very weak and sometimes more or less disappearing (Fig. 5, B). At least some tentacles are radially arranged, but the tentacle area is short in comparison with that described in an earlier paper (Carlgren 1924, p. 66); the arrangement of the mesenteries was cleared up in 1894. I have not seen that the outer tentacles have the appearance which Lesueur had indicated, and it is questionable that these tentacles were correctly figured, although they may have been somewhat branched. This is concluded from an examination of the largest specimen (length and breadth about 2.3 cm.) which was mentioned in 1894. In this specimen the outermost tentacles, which are larger than the others, are somewhat papillous. In general, new tentacles arise towards the mouth with the age of the animals, and doubling of tentacles often occurs in the rows inside the outermost tentacles. The single specimen sent from Grand Isle has not been dissected, as it cannot be expected to provide more information about the arrangement of the mesenteries than already available. A retractor is represented in figure 5, C. The nematocysts of the column are basitrichs. 14–18.3 x ca. 2.2 μ; of the tentacles basitrichs, 16.2–28.2 x 2.2–2.8 μ; of the filaments partly microbasic *p*-mastigophors, 17–21 x 4.2–5 μ, partly basitrichs, 19.7–22.6 x 3–3.5 μ.

The size of the preserved specimen is 1.2 cm., both length and diameter.

Color: In the preserved condition, dull muddy brown. According to Lesueur, yellowish in life.

Distribution: "The Antilles," Louisiana coast.

Remarks: It is very difficult to distinguish the species of *Minyas* from each other; probably there are actually only a few species. The present specimens have been referred to *olivacea* as the species is known from the Antilles. The specimen examined is certainly much younger than the type, but it is certain that the minyads are stichodactylin, and have a more or less developed circumscribed sphincter. Haddon's (1898) description of *Stichophora torpedo* seems to contradict this supposition but his specimen was certainly a very young one, as confirmed by the appearance of the sphincter, which consists only of a single fold, indicating, however, that it may later be developed into a circumscribed one (compare the weak sphincter in our specimens). Therefore I think the diagnosis of the family proposed in Carlgren (1949, p. 71) is correct.

Added note on Minyas olivacea: A living specimen was found on the beach at Port Aransas, Texas, by Martin D. Burkenroad, to whom we are indebted for the following observations. The individual was 6 cm. by 1.5 cm. when expanded; in the contracted state it was about 1.5 cm. in all directions. The color was olivaceous brown with paler stripings. The animal could retract its tentacles completely, and the float does not appear to be an integral part of the animal, but rested like a cap on the pedal disc. When subjected to menthol the animal shed the float and attached itself to the glass of the aquarium when pressed against it. [Unfortunately there is no fertile *Minyas* known, but if these observations are correct it is possible that *Minyas* when full grown has a pedal disc capable of attachment, but it is undoubtedly a distinct genus.]

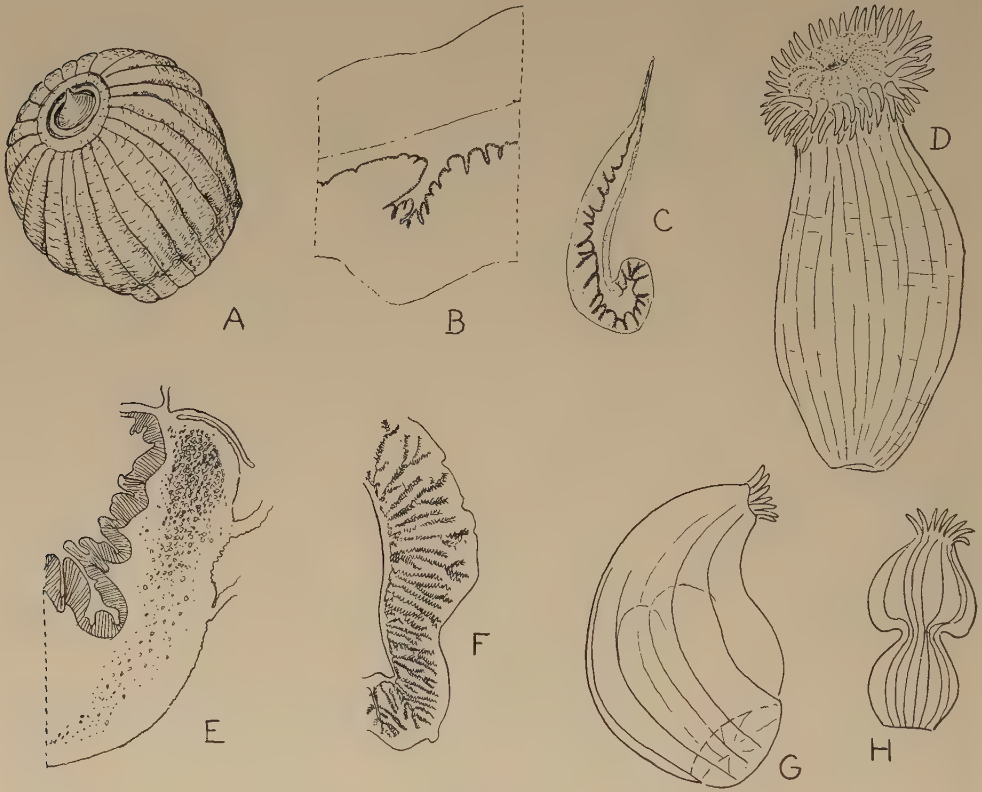

FIGURE 5

A–C: *Minyas olivacea* (Lesueur): A, view of aboral end, showing float enclosed in base; B, sphincter; C, mesentery. D–H: *Paranthus rapiformis* (Verrill); D, sketch of living specimen; E, sphincter; F, mesentery; G, H, sketches of living individual. (E, F, after Carlgren, 1934).

Family ACTINOSTOLIDAE

Paranthus rapiformis (Lesueur)

Plate II; Figure 5, D–H.

Actinia rapiformis Lesueur, 1817, p. 171.

Ammophilactis rapiformis Verrill, 1899, p. 213, figs. 28, 33 (literature).

Paranthus rapiformis Carlgren, 1934, p. 19, figs. 11, 12.

Paractis rapiformis Field, 1949, p. 15, Pl. II, figs. 19, 23–28, Pl. IV, fig. 37.

Material examined: Port Aransas, Texas, 10 fathoms, mud bottom, Jan. 11, 1946, J. W. Hedgpeth, 1 specimen; Port Isabel, ship channel, sandy bottom, March 15, 1947, 2 specimens. J. W. Hedgpeth.

Description: The anatomy of this species is described by Verrill (1899) and Field (1949), and especially by Carlgren (1934). Field notes that there was no sphincter and no filaments in the specimens she examined. As we know that the filaments occur early in the development of the Actiniaria they must certainly have been present in her specimens, and possibly the mesogleal sphincter was also overlooked. Field did not find more than six perfect pairs of mesenteries; probably she did not examine the mesenteries of the oral disc; in a young specimen there are six pairs and two unpaired mesenteries perfect in the lower part of the actinopharynx. The nematocysts of two specimens, one large, and one small and sterile, have been examined. Those of the smaller specimen are enclosed in parentheses: The nematocysts of the column are partly basitrichs, 12.7–14 x 1.5–2 μ (11.3–12.7 x 2.8 μ), partly probably microbasic *p*-mastigophors, 14.1–22.6 x 2.8–5.6 μ (12.7–17 x 2.8–3.5 μ); those of the tentacles partly basitrichs, 18.3–25.4 x 2.5 μ (19–22.6 x 2.5–3 μ), partly common microbasic *p*-mastigophors (probably), 22.6–27.5 x 4.2–4.5 μ (22.6–25.4 x 4.2-4.5 μ); those of the actinopharynx partly basitrichs, 21.1–25.4 x 2.5–3 μ (18.3–21.1 x 2.5 μ), partly *p*-mastigophors or amastigophors, 19.7–24 x (4.2) 5.6–7 μ (19.7–22.6 x 3.5–4.2μ); those of the filaments partly basitrichs, 12.7–14 x 2.2 μ (10.5–14 x 2.2–2.5 μ), partly microbasic *p*-mastigophors, 10–14.8 x 4.2 (5.6) μ (8.5–10.6 (14) x 4.2–5 μ), partly amastigophors (?), 18.3–32.4 x 6.3–7 μ (15.5–26.8 x 4.2–7 μ).

Size of the largest specimen (preserved), 2.3 cm. long by 1.5 cm. in diameter.

Color: Column grayish white or cream, tentacles gray green with warker greener base, oral disc green, with pale salmon markings, transparent between (Port Aransas). In a young specimen from Port Isabel the column was transparent, from colorless to white, oral disc almost colorless with gray splotches and orange mesentery lines (See also Verrill and Field). When brought on deck by the trawlers, these anemones contract to a nearly spherical shape and resemble peeled onions, and are sometimes known as "sea onions" by the fishermen.

Distribution: New Haven, Connecticut; Egg Harbor, New Jersey; Beaufort, North Carolina; Grand Isle, Louisiana. Common in shallow water along the Texas coast.

Remarks: Field states that "the original description of the genus *Paranthus*, Carlgren, 1934, is unobtainable." It is true that the type of *Paranthus (P. cromatoderus)* was not described in the 1934 paper, but it and *P. rapiformis* have been examined (Carlgren 1898, p. 27, also 1949, p. 82), and the genus dates from Andres (1883). The sphincter is rather strong in the sample from Port Aransas. Unfortunately the character of the sphincter in the young specimens from Port Isabel cannot be determined. No distinct sphincter could be made out in the smaller specimen, and the upper part of the second sample was lost during manipulation. However, the sample from Port Isabel is probably *rapiformis* (see below).

Paranthus rapiformis?

Material examined: Barataria Bay, Louisiana. Nov. 2, 1946. E. H. Behre coll. 2 small specimens.

The two very small specimens from Louisiana are very difficult to determine. The types of the nematocysts, especially in the filaments, agree rather well with those occurring in the Actiniaria having two types of nematocysts in the acontia as well as with those present in *Paranthus*,[5] but because no acontia are present (and the acontia seem to develop early, in some forms as early as the larval stage), it is hardly probable that these specimens represent a species with acontia. Probably the specimens can be referred to *Paranthus*, and possibly to *rapiformis*, as the nematocysts agree rather well with those of this species (see below), although no sphincter is developed and the number of tentacles and mesenteries is the same. It is not known at which time the mesogleal sphincter arises in *Paranthus*, or when the mesenteries increase in number in the distal end as against the proximal part of the animal. Probably this differentiation takes place late in *Paranthus*. Nevertheless, a description of these two small specimens is given in the following paragraph.

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[5] It is probable that *Paranthus* must be separated from all the other Hormathiidae and assigned to a new family, Parantheidae, since the nematocysts seem to agree with the forms having two types of nematocysts in the acontia, but the types of nematocysts must be cleared up in living specimens of *Paranthus* before such a new family can be erected. (O.C.)

The body in the preserved condition is cylindrical, the column smooth. There is apparently no sphincter present. The tentacles are rather short, conical and 44 in number in the larger specimen. There are two siphonoglyphs, symmetrically placed. There are six pairs of perfect mesenteries and two cycles of imperfect mesenteries, in all 44 mesenteries at the base. Thus there are apparently the same number of mesenteries at the margin as at the base. Only the first cycle of mesenteries bear filaments. The retractors are present only on the mesenteries of the first cycle, and are diffuse or somewhat restricted. The parietobasilar muscles are weak. The specimens are sterile. In spite of a hard search, no acontia were found. The nematocysts of the column are partly basitrichs, 8.5–12 x 1.5–2 μ, partly probably microbasic *p*-mastigophors (common), 12.7–19.7 x 3.5–4.2 μ; those of the tentacles partly basitrichs (common), 12.7–15.5 x 2.2–2.5 μ, partly *p*-mastigophors or amastigophors, 19–21.8 x 4.5 μ; those of the actinopharynx probably amastigophors, 19.7–22.6 x ca. 4.2 μ; those of the filaments partly basitrichs, 8.5–11.3 x 1.5 μ, partly microbasic *p*-mastigophors, 6.3–12.7 x 4–4.5 μ and 17.6–21 x 4–4.5 μ, partly microbasic amastigophors (?), 26.8–29.6 x 5.6–6.3 μ.

The larger specimen is 0.45 cm. long, 0.2 cm. in diameter.

Color: Pale greenish gray, with darker green lines marking the mesenteries on the oral disc.

Family HORMATHIIDAE

Calliactis tricolor (Lesueur)

Plate II; Fig. 6, A.

Adamsia tricolor McMurrich 1898, p. 234, Pl. 1, figs. 6, 7, Pl. 2, figs. 1, 2.

Calliactis tricolor Haddon, 1898; p. 457; Watzl, 1922, p. 61, fig. 7; Pax, 1924, p. 106; Field, 1949, p. 12, Pl. V, figs. 47–52, Pl. VII, figs. 60, 61, Pl. X, fig. 94. For further literature and synonymy see Andres (1883) and Field (1949).

Material examined: Several specimens from near Port Aransas, Texas, usually on carapace of Calico crab, *Hepatus epheliticus*, 1 specimen on small chip in sand bottomed tide pool. J. W. Hedgpeth, coll.

Description: The anatomy of this species has been described by McMurrich (1898), Field (1949) and especially by Duerden (1902). There is nothing further to add other than the type and size of the nematocysts. The nematocysts of the column are basitrichs, 12–14 x ca. 2.2 μ; of the tentacles, basitrichs, 21–24 x 2.5–3 μ; of the actinopharynx basitrichs, 21–26.8 x 3 μ; of the filaments partly very numerous microbasic *p*-mastigophors, 19–24 x 4.2–5 μ, partly sparse basitrichs, 11.3–12.7 x ca. 1.5 μ; of the acontia basitrichs, 21–26.8 x ca. 3 μ.

Distribution: Beaufort, North Carolina, to Florida; Cuba, Puerto Rico, St. Vincent, Barbados, St. Thomas, Jamaica, Curaçao, Texas.

Color: Column somewhat glossy light brown with white ridges at the base (sometimes white vertical stripes on column) and bright brown cinclides, tentacles pale cream with brown or maroon bands, directive tentacles in one specimen orange. Oral disc pale cream, actinopharynx bright orange with pale magenta shading on disc. Acontia orange (See also Duerden, and Field).

Remarks: This is the most common anemone found along the Texas coast to about 10–15 fathoms; it occurs on the carapace of the calico crab, and on shells carried by the large red hermit crab, *Petrochirus bahamensis*. On the larger shells there may be four or five of these anemones. Off the south Atlantic coast the species has been taken from living shells of *Rehderia georgiana*.

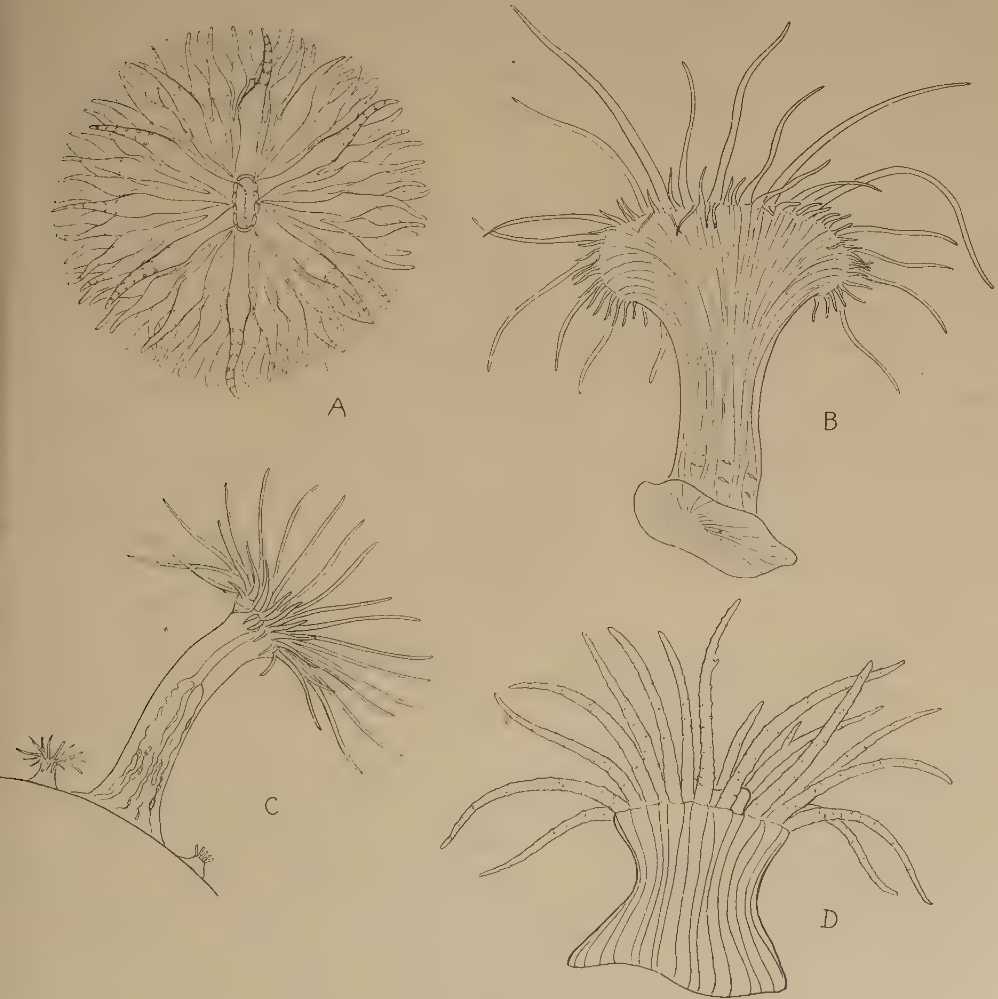

FIGURE 6

A: disc of *Calliactis tricolor* (Lesueur); B–C: sketches of *Aiptasia pallida* (Verrill); D, sketch of juvenile specimen of *Bartholomea annulata* (Lesueur).

In the association with *Hepatus epheliticus,* only one anemone has been observed on a crab. It is located on the middle of the carapace, near the anterior margin. When observed in a small aquarium, the respiratory currents set up by the crab move forward away from the front of the carapace, inducing a converging current from the rear to move forward over the disc of the anemone. It seems probable that when the crab is feeding the anemone may be able to trail its tentacles into the respiratory stream from the crab's mouth and thus pick up bits of food. A similar association between an anemone and a calappid crab occurs on the Chilean coast. In this case the anemone is the actinostolid *Antholoba achates* (Dana) and the crab is *Hepatus chiliensis* M.-E. According to Bürger (1903) there is usually but one anemone on a crab although there may rarely be two, and when separated from its crab in an aquarium, the anemone will eventually orient itself upside down and attach itself to the crab by its upended pedal disc and move to its former position on the middle of the carapace. Bürger was able to perform this experiment twice and concluded that it was the actinian that took the initiative in the association and was the active beneficiary in the association. It would not appear that the crab derives any advantage from this association although it may receive, fortuitously, some protection or concealment from the presence of the anemone on its back.

Family AIPTASIIDAE

Aiptasia pallida (Verrill)

Plate III; Figure 6, B–C.

Dysactis pallida Verrill, 1864, p. 26.

Paranthea pallida Verrill, 1868, p. 322.

Aiptasia agassizii Andres, 1883, p. 391.

Aiptasia sp. McMurrich, 1887, p. 59.

Aiptasia pallida Parker, 1900, p. 755; Carlgren, 1949, p. 107.

Cylista leucolena Field, 1949, p. 13 (in part; also by designation as footnote to table on p. 6!).

Material examined: South Bay, Port Isabel, Texas, on oysters May 15, 1946 (No. 8); North Jetty, Brazos Santiago Pass (Port Isabel), on rocks with *Anthopleura krebsi,* March 20, 1947 (No. 15); Off Port Isabel, 12 fathoms, on old valves of *Atrina* April 2, 1947, small colonies (No. 17). J. W. Hedgpeth, coll.

Description: The pedal disc is rather well developed but of smaller diameter than the oral disc. The body is more or less pillar-like with cinclides arranged in one or two circles about in the middle of the column. In the contracted state the column forms a parapet above the cinclides as in many other species of *Aiptasia,* dividing the column indistinctly into scapus and capitulum. The margin is tentaculate. The sphincter is rather long, consisting mostly of a single row of meshes situated in the middle of the mesoglea. The tentacles are smooth, not retracted, up to about 97 in number, the inner long, the outer shorter. There are two siphonoglyphs and two pairs of directives. Three examined specimens had six pairs of perfect mesenteries. In a sectioned, small specimen from 12 fathoms the lateral perfect mesenteries were considerably weaker than their partners, indicating that the individual had arisen by laceration (constriction). The retractors of the perfect mesenteries are strong, diffuse, the parietobasilar muscles weak. The nematocysts of the column are partly basitrichs (common), 14–18.3 x 2.5 μ (11.3–19.7 x 2.2–3 μ, 10–14 x 2.2–2.5 μ); partly microbasic *p*-mastigophors, 18.3–24 x 4.2–5 μ (17–22.6 (25.4) x 4.2–5.6 μ; 17–19.7 x 4.5–5 μ); those of the tentacles partly basitrichs, 14.8–19.7 x 2.8 μ (14–18.3 x 2.2–2.5 μ; 12.7–17 x 2.2–2.5 μ); partly microbasic *p*-mastigophors 24.7–34.5 x 4.2–5 μ (24–29.6 x 3.5–4.2 μ; 26.8–32.4 x 4.2–5.6 μ); those of the actinopharynx partly basitrichs, 9.2–17.6 x 1.5–2.8 μ (———; 10–14 x 2.2–2.5 μ); partly microbasic amastigophors, 22.6–31 x 4.2–5 μ (19.7–24 x 3–3.5 μ; 17–22.6 x 3.5–4.2 μ); those of the filaments partly basitrichs (few), ca. 17 x 2.8 (14–15.5 x 2.5 μ; 10–14 x 2.8 μ); partly microbasic *p*-mastigophors, 10–17 x 3.5–4.5 μ (11.3–15.5 x 3 μ; 10–18.3 x 4.2–4.5 μ), and 29.6–36.7 x 5.6–7 μ (32.4–36.7 x 4.5–5.6 μ; 29.6–39.5 x 5.5–5.6 μ); those of the acontia partly microbasic *p*-mastigophors, 60.6–75.4 x 7–8.5 μ (48–66.7 x 5.5–7 μ, 58–67.7 x 6.3–7.7 μ), partly basitrichs, 22.6–26.8 x 2–3 μ (29.6–35.3 x 2.2–2.5 μ, 17–19.7 x 2.2–2.5μ). The nematocysts of three specimens were measured, the first from lot No. 8, the other two (in parentheses) from No. 15, and a small specimen from No. 17.

The largest specimen (from lot No. 8) measured 1.5 cm. in length, the diameter of the oral disc about 1.3 cm., of the pedal disc 0.8 cm.

Color: Column brown, striped with darker brown, tentacles deep reddish brown to pale chocolate, oral disc various combinations of brown and cream or brown-cream white, acontia white (Lot No. 8—see Plate III). Tentacles gray-cream, oral disc pale red-brown (No. 15). Column transparent, revealing the pale yellow brown viscera, tentacles powder blue, fading toward the transparent disc (No. 17).

Distribution: North and South Carolina. Cameron, Louisiana jetty (Cary, 1906). Although very abundant on oysters in South Bay near Port Isabel, and occurring sparsely on the nearby jetties, this anemone was not collected in Aransas Bay or from the Port Aransas area during the years 1945–1949. The powder blue phase has been collected only offshore in the Port Isabel region on the Texas coast.

Remarks: In the ectoderm of the tentacles in a specimen from Lot No. 8 there are numerous round or oval bodies, probably gregarines.

In 1947 a dozen or so of these anemones were transported to Rockport and maintained in battery jars for several weeks. Within a short time very small individuals appeared on the walls of the jars. The animals withstood the concentration of sea water resulting from as much as an inch and a half to two inches evaporation, and when the original level was restored by the addition of distilled water, showed no ill effects. Attempts to acclimate them to local Aransas Bay water were, however, unsuccessful. The addition of bay water to a jar whose level had dropped an inch caused all the anemones in that jar to die within a few hours. The anemones are cannibalistic—if the term may thus be broadly used—eating not only their own species, but other anemones as well. A specimen of *Bunodosoma cavernata*, dropped into a jar, passed too near the expanded disc of an *Aiptasia* and was almost instantaneously engulfed in a spasmodic motion. It should be noted that this habit may lead to nematocyst contamination, especially if a number of different live anemones are placed in the same collecting receptacle.

Bartholomea annulata (Lesueur)

Figure 6, D.

Actinia annulata Lesueur, 1817, p. 172.

Aiptasia annulata McMurrich, 1889, p. 7, Pl. 1, fig. 1; Duerden, 1902, p. 355, Pls. III, XI, XII, figs. 11, 41–44; Pax, 1910, p. 206; Weill, 1934, p. 578, figs. 60, 131, 386, 388, 389.

Bartholomea annulata Stephenson, 1920, p. 532; Watzl, 1922, Pax, 1924, p. 107, fig. 12; Carlgren, 1949, p. 108.

Material examined: From sargassum, St. Joseph Id., Texas, April 8 1946; several specimens. J. W. Hedgpeth, coll.

Description: The specimens taken from sargassum are all very young, but the tentacles have the typical appearance for *Bartholomea*. The species has been previously described by McMurrich and Duerden, especially the latter. The nematocysts of these specimens are considerably smaller than in the full grown individuals. The microbasic *p*-mastigophors of the tentacles are 26–32.4 x 3.5–4.2 (5) μ, the basitrichs 8.5–12.7 x ca. 2 μ; the microbasic *p*-mastigophors of the filaments are partly 21–28 x 4.2 μ, partly 4.2–8.5 x 2.8 μ, oviform, the basitrichs 7.7–10 x 2 μ.

Color: Transparent white, or faint brown with a thin blue border around the mouth.

Distribution: Bermuda and the Bahamas, Puerto Rico, Jamaica, St. Thomas, Guadeloupe, Barbados, Curaçao, Texas.

Family AIPTASIOMORPHIDAE

Aiptasiomorpha luciae (Verrill)

Plate IV; Figure 7, A.

Sagartia luciae Verrill, 1898, p. 493.

Diadumene luciae Stephenson, 1925, p. 888, fig. 1, F; Uchida, 1932; Stephenson, 1935, p. 197, figs. 75, 79 (literature); Carlgren, 1945, p. 19; Field 1949, p. 10.

Aiptasiomorpha luciae Carlgren, 1949, p. 109.

Material examined: Lydia Ann Channel, Port Aransas, Texas, March 1, 1948. 4 specimens. J. W. Hedgpeth, coll.

The specimens are small. The nematocysts of the tentacles and filaments agree very well in size with those found in a small individual from Busum (Carlgren, 1945, p. 19). The largest specimen (preserved), is 0.6 cm. high by 0.7 cm. largest diameter.

This species is not synonymous with *Diadumene cincta*, and in the survey paper (Carlgren, 1949) was referred to *Aiptasiomorpha*, but the definite name of the genus cannot be decided until the type of the genus *Diadumene, D. schilleriana*, is examined. It is, however, very probable that *D. cincta* and *D. schilleriana* are not referable to the same genus.

Distribution: See Stephenson (1935) and Carlgren (1949); also the comments in the introduction to this paper.

Remarks: It would appear, from the wide range of salinities represented by the localities from which this species has been reported, that salinity is not the limiting factor in its distribution. This has been demonstrated experimentally by Miyawaki (1951), who found that specimens could survive in distilled water for two days, for 12 days in a mixture of ⅛ sea water and distilled water, and indefinitely in a ⅜ concentration of sea water. At the other end of the salinity spectrum, specimens lived in salinities of about 74°/oo for four days without previous acclimation. Such extremes are well outside the ranges in which this species is found in nature.

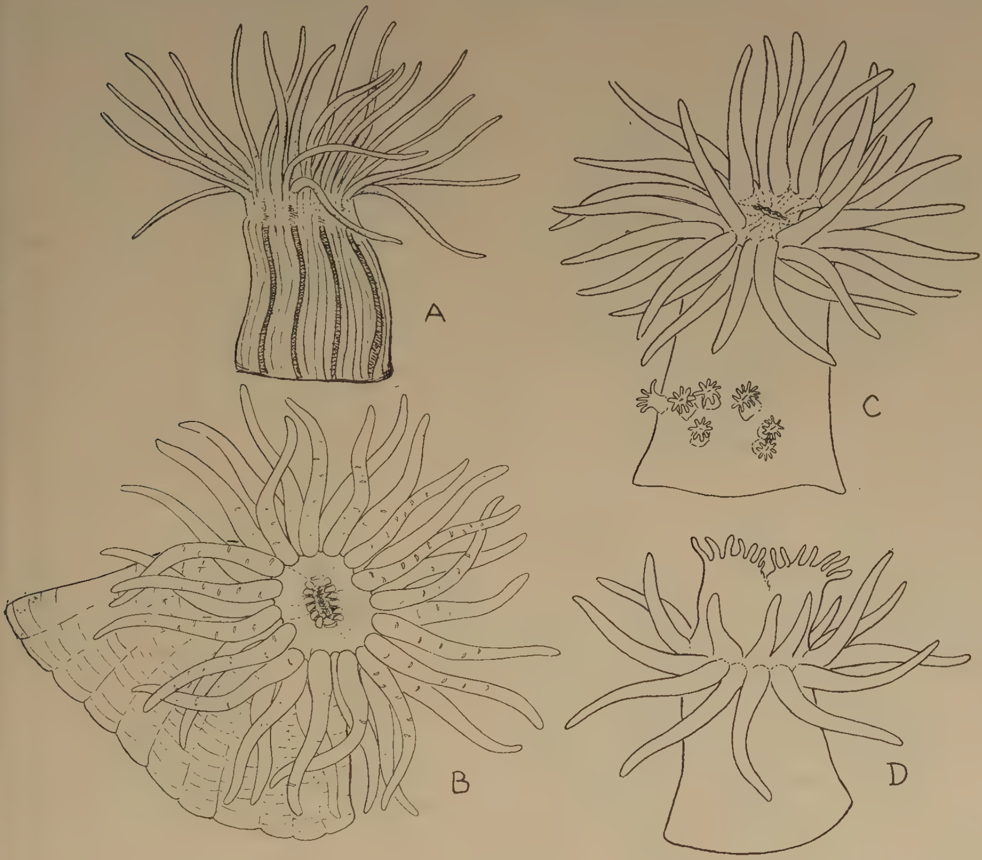

FIGURE 7

A: *Aiptasiomorpha luciae* (Verrill); B–D: *A. texaensis,* n. sp.; various views, showing asexual reproduction; the base of B is about 3 mm wide.

Aiptasiomorpha texaensis n. sp.

Figure 7, B–D.

Material examined: Rockport, Texas, among bryozoan on piling (3 specimens) Nov. 13, 1945; Port Aransas, Texas, from shell of live oysters, 2 specimens; on oysters, Bay Chêne Fleuri, Louisiana, Sept. 9, 1947, 1 specimen. (All coll. by J. W. Hedgpeth), (Holotype, U.S.N.M. No. 49993, from oyster, Rockport, Texas, Nov. 13, 1945).

Description: The pedal disc is well developed; the column apparently divisible into scapus and capitulum. In the contracted state the capitulum is somewhat drawn into the scapus. A ring of cinclides is present, about in the middle of the column. A sphincter is apparently absent. In four specimens sectioned, no traces of a mesogleal sphincter were found, but the endodermal muscles of the column are fairly well developed. The tentacles are long, somewhat more than 30 in number, apparently not retractile, the inner tentacles at least half as long as the length of the column. There are two distinct siphonoglyphs, and six fertile pairs of mesenteries, among them two pairs of directives. The retractors of the perfect mesenteries are restricted, the imperfect mesenteries of the second order are considerably weaker than the perfect mesenteries, but some of them at least are provided with filaments. The species probably reproduces by laceration, as young individuals have been observed on the column of one specimen (J.W.H.).

The nematocysts of the specimen from Louisiana, and of a specimen from Port Aransas and from Rockport (the latter two indicated in parentheses) have been examined. The nematocysts of the column are partly basitrichs, 11.3–15.5 x 2.2–2.8 μ (12–12.7 x 2.5 μ; 9.2–14 x 1.5–2.8 μ), partly *p*-mastigophors or amastigophors, 10.6–14.6 x 3.5–4.2 μ (11.3–15.5 x 3.4–4.2 μ; 12–18.3 x 4–5 μ); those of the tentacles partly basitrichs, 12.7–17.5 x 1.5–2 μ (13.4–15.5 x 1.5 μ; 12.7–15.5 x 2 μ), partly microbasic *p*-mastigophors or amastigophors, (17) 21–24 x 4.2 μ (19.7–21 x 3.5–4 μ; 18.3–22 x 3.5–4 μ); those of the actinopharynx partly microbasic *p*-mastigophors or amastigophors, 17–21 x 3.5 (17–22.6 x 3.5–4 μ; 19–21.8 x 3.5–4.2 μ) partly a few basitrichs, 15.5–17 x 1.5–2.2 μ (12.7–14.1 x 1.5 μ; 12.7–15.5 x 1.5–7.5 μ); those of the filaments partly microbasic *p*-mastigophors, 6.3–12.7 x 3.5–4.2 μ (6.3–13 x 3.1–4.2 μ; 7.7–19.7 x 3.5–4.2 μ), partly microbasic *p*-mastigophors or amastigophors. 18.3–22.6 x 3.5–4 μ (17–21 x 3.5–4 μ; 15.5–21 x 3–3.5 μ), partly, a few basitrichs, possibly, from the acontia, 14–15.5 x 1.5 μ (10–12.7 x 1.5 μ; 11.3–12.7 x 1.5 μ); those of the acontia partly basitrichs, 12.7–17 x 1–2 μ (15.5 x 1.5 μ; 11.3–12.7 x 1.5 μ), partly *p*-mastigophors or amastigophors, 28.2–31–7 x 5–7 μ (21.8–25.4 x 5.6–7 μ; 26.8–31.7 μ x 5.6–7 μ). It has been impossible to determine, from the available material, whether the larger nematocysts of the acontia are mastigophors or amastigophors.

The animals are 0.5–0.6 cm. in diameter.

Color: Very pale orange cream or salmon pink, with gray center in the tentacles.

Remarks: The specimens were not well preserved, but as there is apparently no sphincter, they cannot at present be referred to *Aiptasia*, which they resemble. Possibly the absence of a sphincter is associated with the small size of the specimens, but as the primary mesenteries are fertile and specimens of *Aiptasia* of about the same size or a little larger show a distinct mesogleal sphincter, it seems hardly probable that this species should develop a mesogleal sphincter in a more advanced stage. Although it cannot be decided whether there are microbasic *p*-mastigophors or amastigophors in the acontia, it is suggested nevertheless that they are *p*-mastigophors (O.C.). As no sphincter is present, the species may at present be referred to *Aiptosiomorpha*.

A few of these small anemones were also collected in Copano Bay. There occurrence here and in Louisiana waters indicates that this species is a form tolerating salinities as low as 9–10 0/00. It was not observed at Port Isabel, where the salinities in South Bay are usually above 30 0/00 and and the record from Port Aransas is from oysters in experimental trays moved from Copano or Aransas bays a short time before.

Family SAGARTIIDAE?

Genus **Botryon** n. gen.

Column provided with tubercles (thickenings of the mesoglea), more or less regularly arranged in longitudinal rows. Sphincter mesogleal. Tentacles short, not very numerous. Two distinct siphonoglyphs and two pairs of directives. Twelve pairs of mesenteries perfect. All, or almost all, mesenteries fertile. The male sexual organs grape-like. Retractors of the perfect mesenteries well developed. parietobasilar muscles weak. Acontia present, their nematocysts basitrichs and probably microbasic amastigophors (until the latter are decided with certainty the systematic position of this genus cannot be decided).

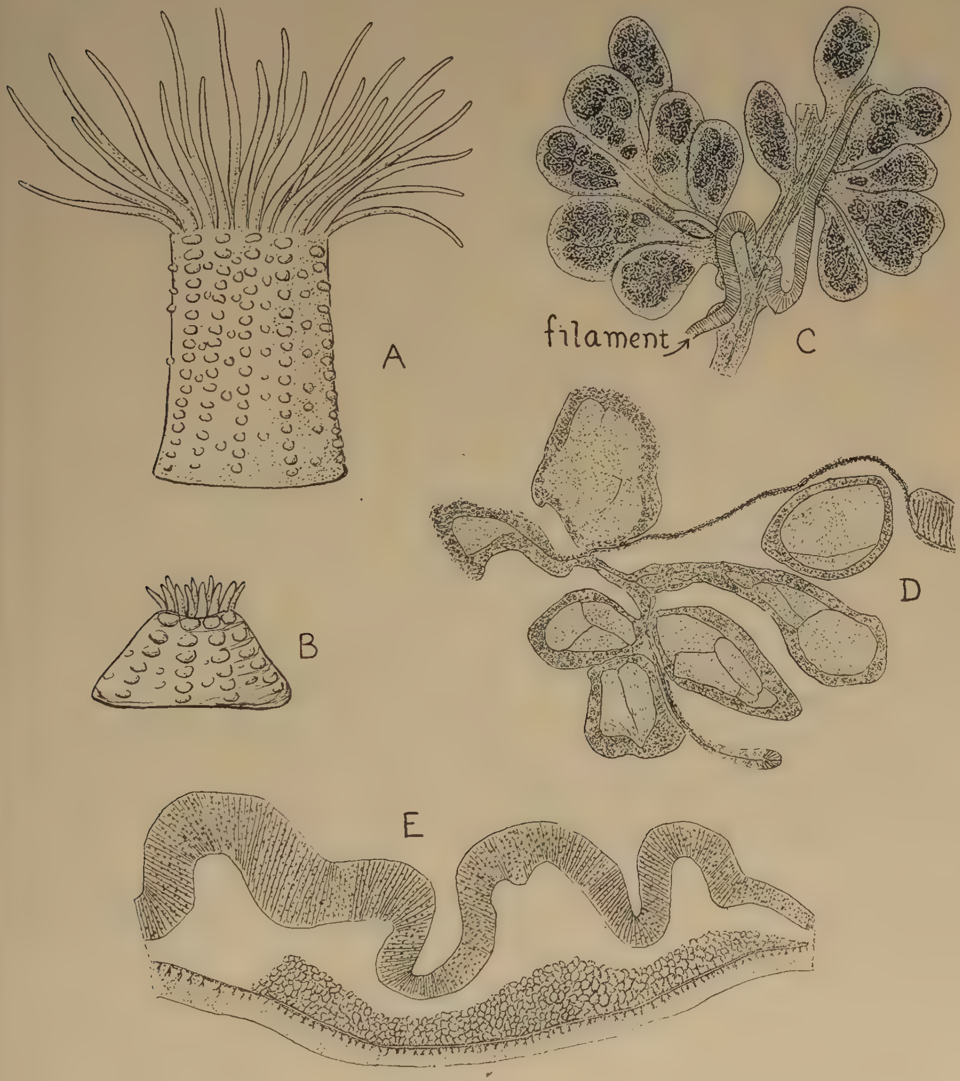

FIGURE 8

Botryon tuberculatus, n. gen., n. sp.; A, B, sketches of living specimen; C, part of a mesentery showing the botryoidal clusters and the filament; D, section of a mesentery showing male organs and a part of a retractor; E, sphincter.

Botryon tuberculatus n. sp.

Plate IV, Figure 8, A–E.

Material examined: Ship Channel, Port Isabel, March 27, 1947. 1 specimen. sandy bottom. J. W. Hedgpeth, coll. (Holotype, U. S. N. M. No. 49999.)

Description: The body in expanded state cylindrical, the pedal and oral discs of about the same diameter in the contracted states; the pedal disc is, however, somewhat wider (Figure 8B). The column is provided with papillae, showing a distinct tendency to be arranged in longitudinal rows, distinctly visible on a sketch of the living specimen (Figure 8, A–B). The papillae are thickening of the mesoglea, but their ectoderm is more compact than the other ectoderm of the column. There are, however, no foreign bodies attached to the papillae in the single specimen. The sphincter is well developed, mesogleal, reticular, occupying about half of the thickness of the mesoglea and separated from the endodermal muscles of the column by a thin mesogleal lamella (Figure 8, E). The tentacles are short, conical, the inner longer than the outer and between 70–80 in number. The actinopharynx is longitudinally furrowed and there are two distinct siphonoglyphs. The perfect pairs of mesenteries are twelve in the uppermost part of the ectinopharynx, six in the lower part. All—or almost all—of the mesenteries are fertile. Of particular interest is the appearance of the male organs, which form *botryoidal clusters* (Figure 8, C), not previously observed in any actiniarian, but somewhat suggestive of the arrangement of the reproductive organs in the Ptychodactiaria. The retractors of the mesenteries are restricted (Figure 8D) and of about the same appearance as those in *Aiptasia;* the parietobasilar muscles are weak. The nematocysts of the column are partly basitrichs, 13.3–14 x 2.2–2.5 μ, partly (12.7) 14.8–17 x 3.5–4 μ, opaque *p*-mastigophors or amastigophors; those of the tentacles partly basitrichs (12.7) 14–15.5 x 2.2–2.5 μ, partly *p*-mastigophors or amastigophors, 15.5–19 x 3–3.5 μ; those of the actinopharynx partly numerous basitrichs, 19.7–24 x 2.5–2.8 μ, partly microbasic *p*-mastigophors, 15–19.7 x 3.5–4.5 (5) μ; those of the filaments partly numerous microbasic *p*-mastigophors, 10–12.7 x 4.2–5 μ, partly probably *p*-mastigophors, 18.3–21 x 3.5–4.2 μ; those of the acontia partly basitrichs, 21–26.2 x 2.8 μ; partly probably amastigophors, 26.8–32.4 x 4.2–5 μ (the shaft in the unexploded capsules is about 2/3–3/4 the length of the capsules).

Size, in the expanded, preserved state: Body, 1.2 cm. long, diameter of the base 0.45, at the margin 0.5. Length of the inner tentacles, 0.3 cm.

Color: Tentacles pale green cream, center of oral disc violet, the base of the tentacles of cycles 1–3 olive green, disc at the base of cycle 4 pale orange (Plate IV).

Order ZOANTHARIA

Family ZOANTHIDAE

Palythoa texaensis n. sp.

Figure 9, A–C.

Material examined: Port Isabel, Texas, 10–12 fathoms, on old shells. April 1, 1947. 3 specimens. J. W. Hedgpeth, coll. (Holotype, U. S. N. M. No. 49989.)

Description: Three small polyps, not connected by a coenenchyme. The column is very strongly incrusted with sand grains, occupying the whole mesoglea. There are 14 distinct scapular ridges. The ectoderm of the column is thin and discontinuous, its cuticle weak. The mesoglea is thick and provided with numerous cells and cell-islets, the latter situated near the endoderm, which is thinner than the ectoderm (Figure 9, C). The mesogleal sphincter forms a single row of large muscle meshes (Figure 9,B). The tentacles are small, 28 in number in the largest specimen. There is no distinctly marked siphonoglyph, but its cilia are apparently stronger than in other parts of the actinopharynx, the mesoglea of which contains rounded granulous cells. There are 28 mesenteries, regularly arranged. The perfect mesenteries are thin, the imperfect thick and rounded, their mesoglea containing numerous granulous cells, usually strongly packed and probably lying in canals, but owing to the smallness of the mesenteries it was difficult to observe and it could not be determined that there was actually a canal system. The longitudinal and parietobasilar muscles form a straight lamella. The specimens are sterile. The nematocysts of the tentacles are microbasic *b*-mastigophors, 18.3–22.6 x 2.8–3.5 μ; those of the actinopharynx *b*-mastigophors, 31–33.8 x ca. 4 μ; those of the filaments partly microbasic *p*-mastigophors, 17–19.7 x 3.5–4.2 (5) μ, partly *b*-mastigophors, 28.2–38.4 x 4.2–5 μ; partly holotrichs (only one nematocyst found), 25.4 x 10 μ. The sparseness of the holotrichs may possibly be characteristic of the species.

Length of the largest polyp, 1.2 cm., diameter at the margin, 0.5–0.4 cm.

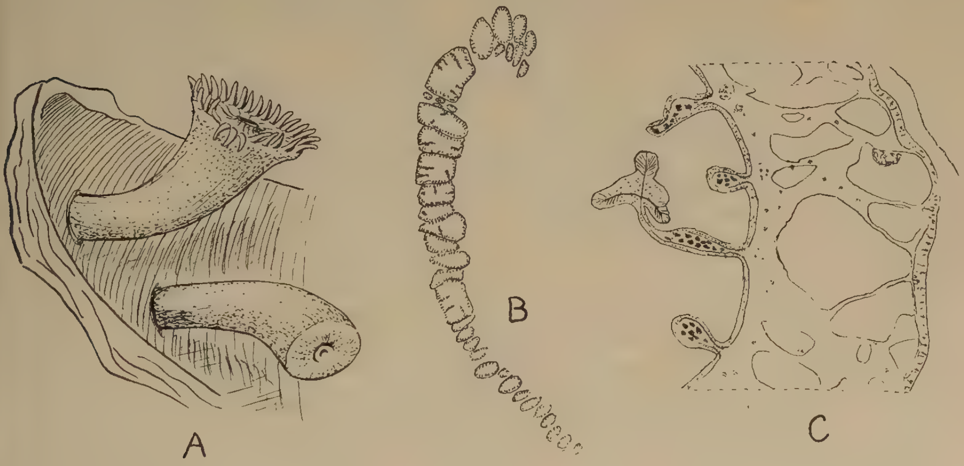

FIGURE 9

Palythoa texaensis n. sp.; A, sketch of living individuals on bit of old shell; B, sphincter, C, section of column wall showing structure of mesoglea.

Order CERIANTHARIA

Family CERIANTHIDAE

Ceriantheomorphe brasiliensis Carlgren

Plate IV.

Ceriantheomorphe brasiliensis Carlgren, 1931, p. 2, figs. 1–5; Carlgren, 1940, p. 12.

Material examined: 20 miles S. of Port Aransas, Texas, off Corpus Christi Pass, 14 fathoms, Nov. 7, 1945, W. Close, coll.; 1 specimen, in try net; 10 miles north of Huts Bayou, Mexico, 14 fathoms, W. W. Anderson, coll. (upper part of specimen).

These two specimens have been identified with this species although their habitat is far from that of the type. One specimen is well preserved and entire, the other consists of only the upper part of the body with the actinopharynx. Unfortunately the nematocysts of the holotype were not measured, and it is possible that these specimens may represent another species, but in both cases they are very closely related to the type. The long marginal tentacles are very numerous. The arrangement of the mesenteries and their filaments agrees with that found in the type (see Carlgren, 1931, fig. 2), except that the plectocraspedon (cnidoglandular tract of the filaments) of the protomesenteries 3 and the metamesenteries B and b are considerably stronger. In both specimens there is a directive labial tentacle present. Four mesenteries are attached to the siphonoglyph in the well preserved specimen, in the other there seem to be more than four, but it is difficult to determine the exact limit of the siphonoglyph. All mesenteries, except probably the youngest in the multiplication-compartment, are fertile. The arrangement and size of the nematocysts in the two samples agree rather well. The nematocysts of the incomplete specimen are given in parentheses. The nematocysts of the column are partly atrichs, very common, 37–69 x 9–21 μ (25.5–59 x 6–21 μ), partly fairly common holotrichs, 49–56.5 x 10–11.3 μ (44–60.5 x 8.5–12 μ partly hoplotelic *b*-mastigophors, 29.5 –46.5 x 7–8.5 μ (31–42.3 x 5.5.–10 μ), partly *b*-mastigophors (not hoplotelic), 21–31 x 3.5–4 μ (24–35 x 4 μ); those of the marginal tentacles partly hoplotelic *b*-mastigophors, 32.4–42.3 x 5–10 μ (32.4–42.3 (70) x 5–5.6 (10) μ), partly not-hoplotelic *b*-mastigophors, 22.6–26.8 x 3–4 μ (19.7–26.8 x 2.8–3.5 μ), partly a few atrichs (33.8–42.7 x 6.3–11.3 μ); those of the labial tentacles partly hoplotelic *b*-mastigophors, 36.7–53.6 x 4.5–10 μ (29.6–43.7 x 4.2–7.8 μ), partly not-hoplotelic *b*-mastigophors, 19.7–25.4 x 3 μ (19.7–26 x 3.5 μ); those of the actinopharynx partly hoplotelic *b*-mastigophors, 38–63.5 x 5–10 μ (38–52 x 5–10 μ), partly not-hoplotelic *b*-mastigophors 26.8–35.2 x 4 μ (22.5–38 x 3.5–4.2 μ), partly atrichs, 41–53.6 x 6.3–8.5 μ (31–38 x 5.6–7 μ); those of the plectocraspedon hoplotelic *b*-mastigophors, partly 18.3–31 (42.3) x 4.5–7 μ, partly 21 x 3.5 μ; those of the orthocraspedon (ciliated tracts), hoplotelic *b*-mastigophors (rare), 46.5–63.5 x 8.5–12 μ. The smallest, not hoplotelic *b*-mastigophors have a short shaft, the hoplotelic, larger mastigophors (probably two sorts) have a long shaft or one of intermediate length.

The complete specimen is 21 cm. long, about 4 cm. in largest diameter, the marginal tentacles up to 6 cm. long.

Color: (Of the complete specimen) Preserved, the column and actinopharynx are olive brown, oral disc yellowish brown, the tentacles colorless. This specimen, when freshly dead, was a rich sepia brown on the column with brown striping on the outer parts of the tentacles; the inner tentacles were bright salmon (See Pl. IV).

Distribution: Previously known from St. Sebastian, Brazil.

Remarks: Cary (1906) and other workers at the old Gulf Biologic Station at Cameron, reported colonies of a *Cerianthus* on the Chandeleur Islands. Unfortunately the animal has not been collected recently, and it is not known whether the colonies are still extant, and the identity of the species cannot be ascertained at this time. The burrowing habit of these animals makes it difficult to collect them with ordinary gear, and it is possible that they may be more abundant than these collections indicate. The occurrence of colonies of cerianthids, which may form vertical burrows over an inch in diameter and perhaps two feet deep, lined with mucous sheaths. should have noticeable effects on layering of sediments. Under certain conditions, the tube might become filled with a sediment different from that in which the tube is formed following the death of the animal. This would result in a long, core-like cast.

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PLATE I

Upper left: *Anthopleura krebsi* (Duch. et Mich.); upper right: *Bunodactis texaensis* n. sp.; lower: *Bunodosoma cavernata* (Bosc), oral view of typical coloration and lateral view of another color phase.

PLATE II

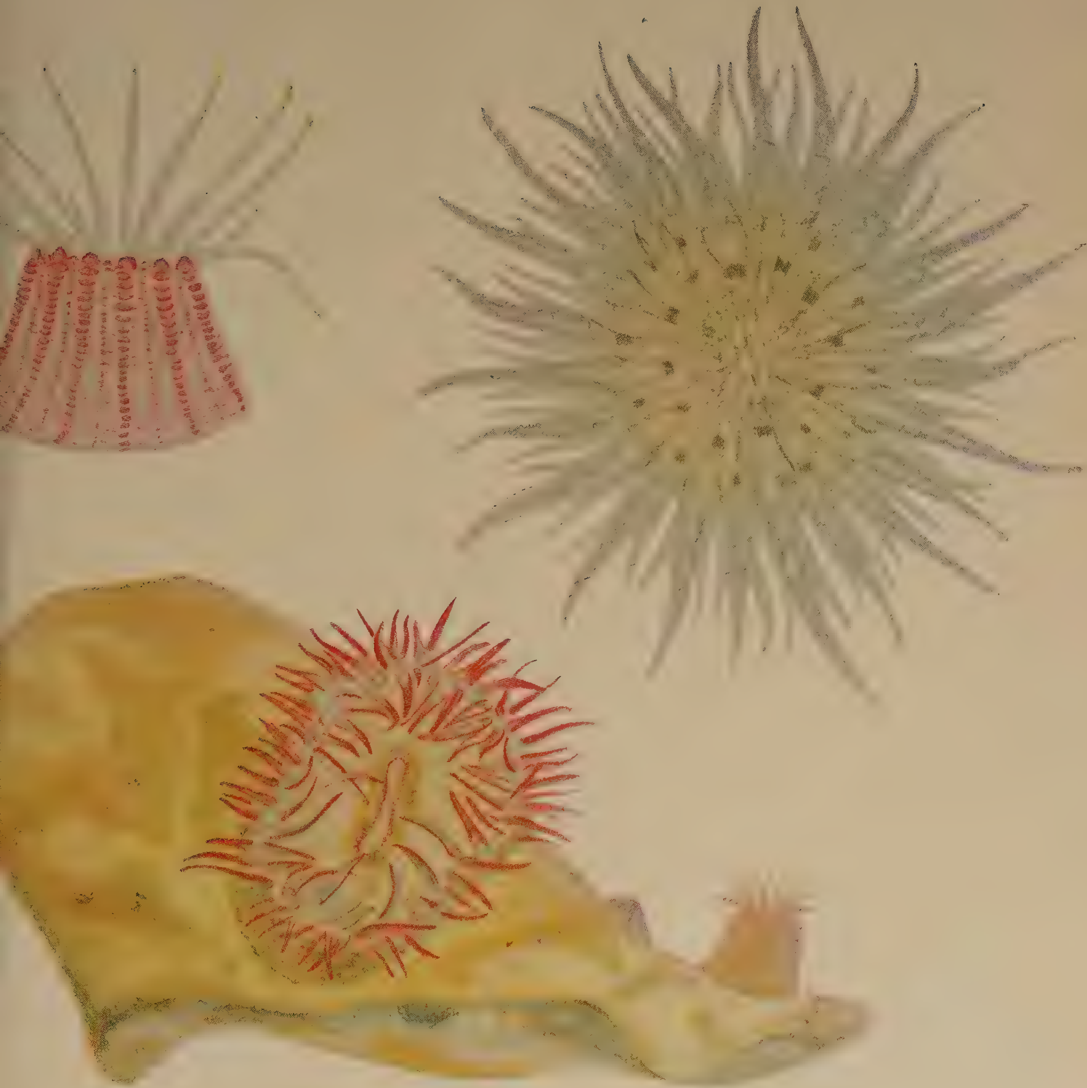
Upper left: *Paranthus rapiformis* (Verrill); upper right: *P. rapiformis,* disc of small individual from Port Isabel; lower left: disc of *Botryon tuberculataus* n. gen. et sp.; lower right: *Calliactis tricolor* (Lesueur) on carapace of *Hepatus epheliticus.*

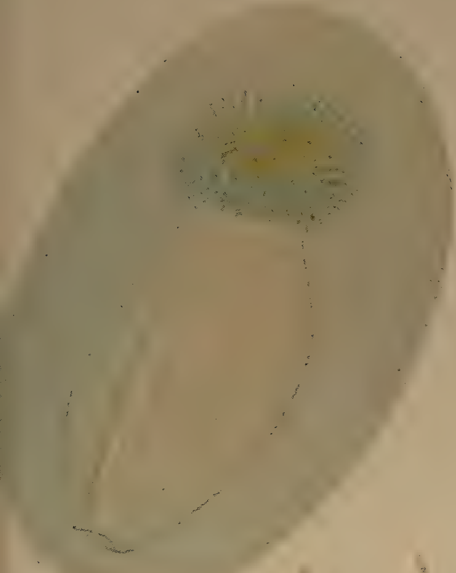
PLATE III

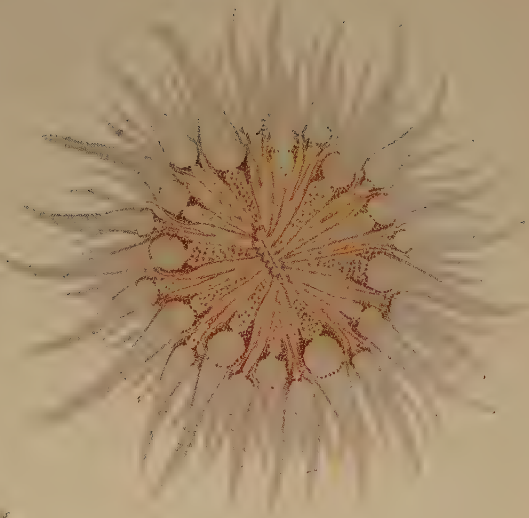
Aiptasia pallida (Verrill); specimens from South Bay, Port Isabel.

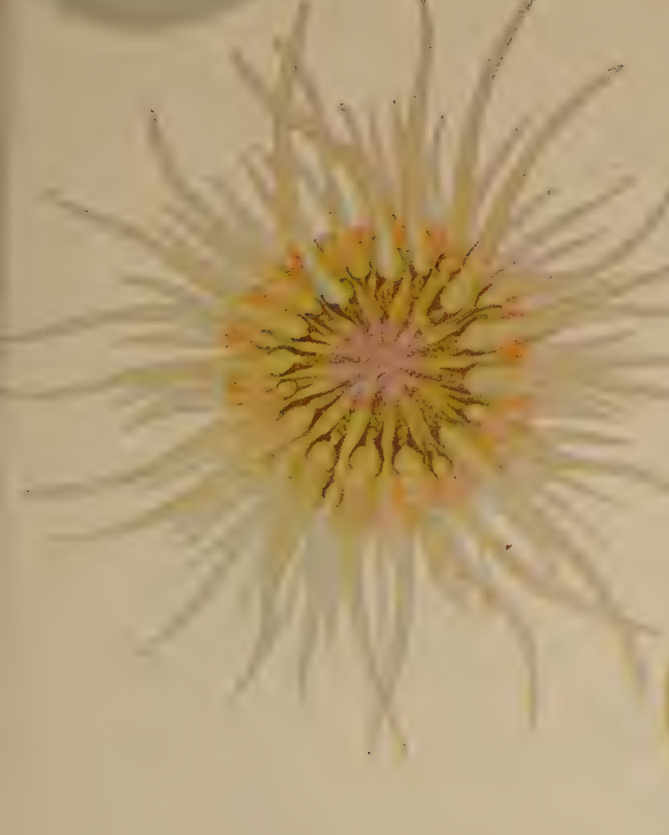
PLATE IV

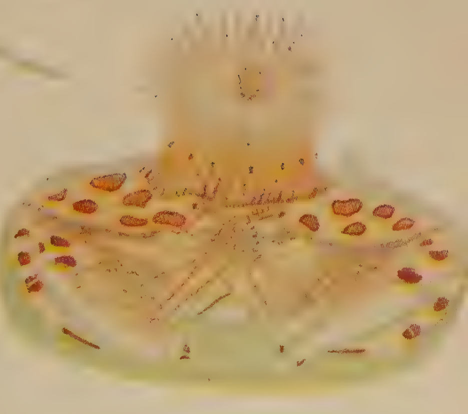
Upper: *Aiptasiomorpha luciae* (Verrill); lower left: *Anemonia sargassensis* Hargitt, lower right: *Ceriantheomorphe brasiliensis* Carlgren.

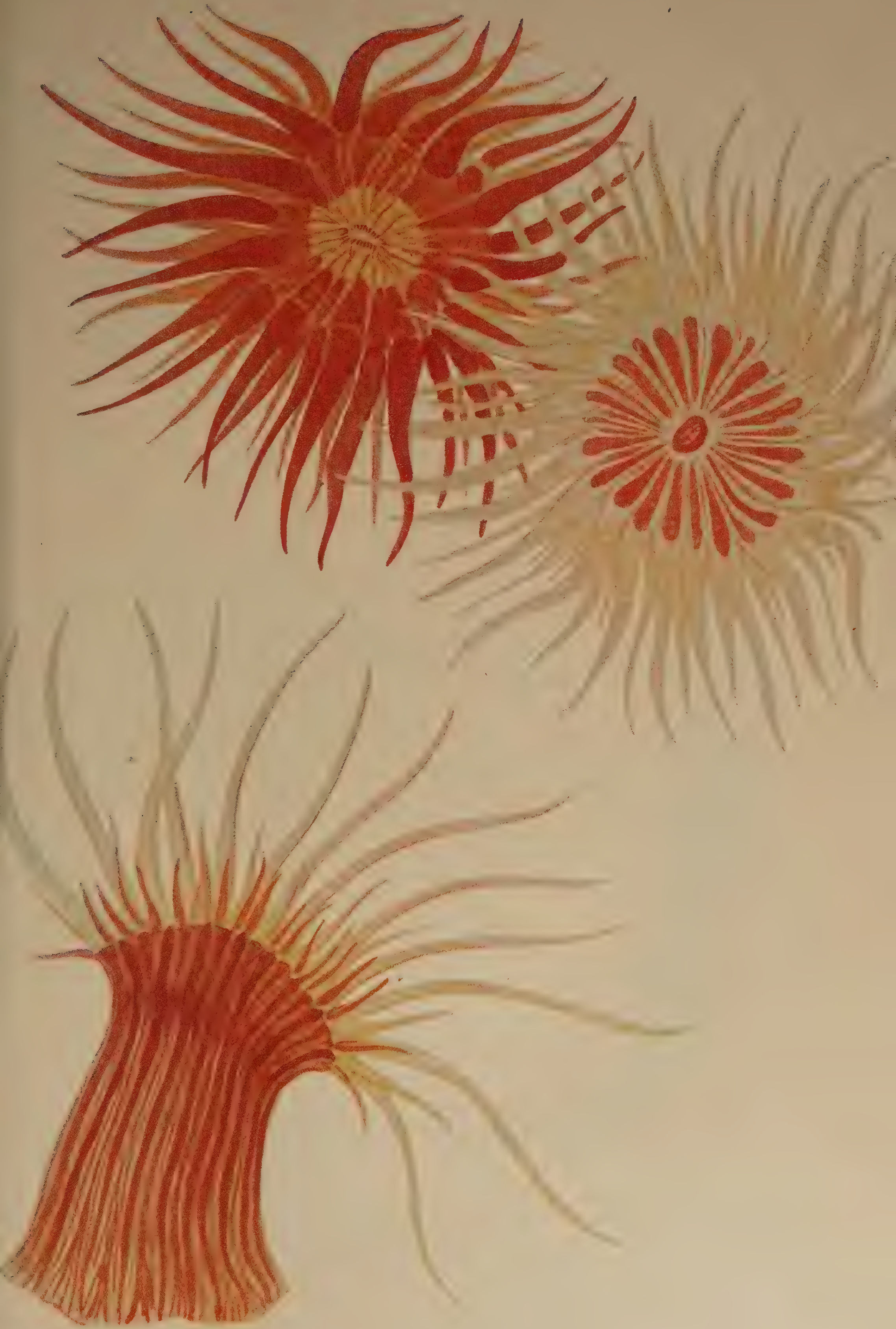


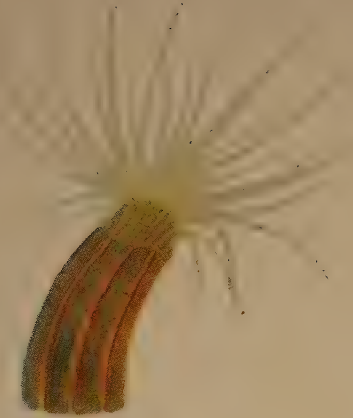


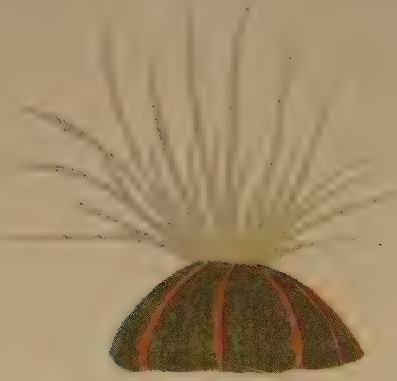


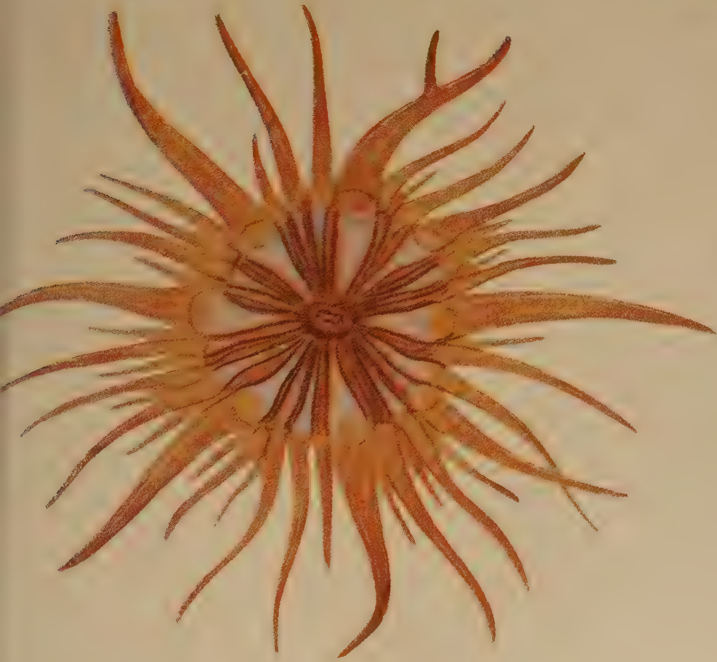


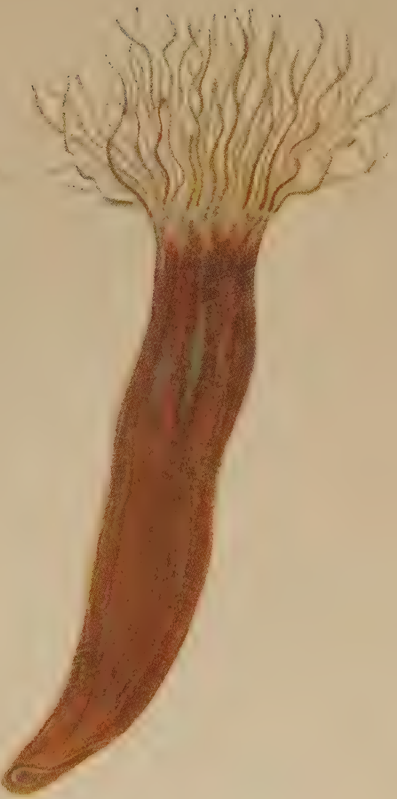


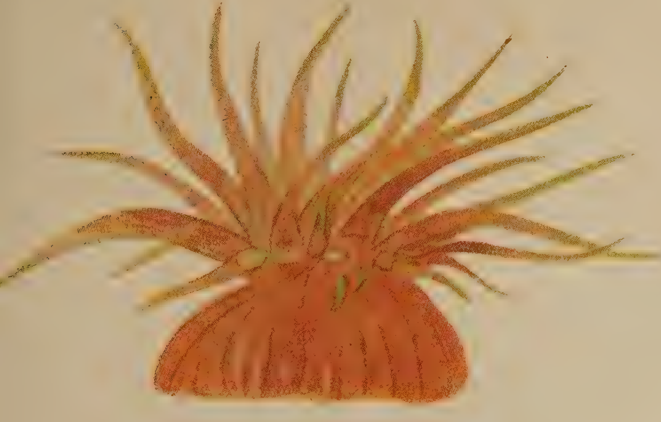












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SUBMARINE GEOLOGY OFF SAN DIEGO, CALIFORNIA[1]

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ABSTRACT

The coast in the vicinity of San Diego is bordered by a shelf only 5–10 miles wide. Near the southern limit of the area, several small islands rise from the outer part of the shelf. These islands have a submarine extension to the north as a low ridge that is cut by a transverse canyon. North of the canyon the ridge forms an isolated, flattened bank that continues as a narrow ridge northward into deep water. Separating the bank and deep ridge from the shelf is a submarine valley having a "drainage" divide in the southern end. North of the divide the valley floor slopes northwestward into San Diego Trough. South of the divide the valley slopes southward, meeting the transverse canyon at a point east of the ridge. An escarpment just west of the islands and the bank forms one side of a deep graben-like depression known as San Diego Trough. A delta-like feature at the mouth of the canyon extends from the foot of the escarpment partway across the floor of San Diego Trough. The relationship of the transverse and longitudinal valleys and of the flat-topped "delta" may provide new information on the origin of submarine canyons.

On the inner part of the shelf south of Point Loma is an area of outcropping Cretaceous shale and sandstone only partially covered with unconsolidated sediment. The bank top has another large tract of bedrock that consists of sandstone and shale of late Pliocene to late Pleistocene age, overlain in part by nodules of phosphorite which are Pleistocene to Recent in age. Rock cropping out on the shelf around the islands is lithologically similar to the Miocene rocks of the islands.

Gravels are abundant in the various areas of bedrock outcrops and also are present in some areas where no bedrock is known. One tract of boulders and cobbles with only interstitial sand occurs a mile off the mouth of the Tia Juana River; similar gravels, but with much more sand, form an elongate area south of Point Loma. Most of the gravels are covered by delicate growths, showing that they are not being moved at the present time. Possibly they are residual deposits formed during times of glacially lowered sea-level.

The finer sediments that partially blanket the sea floor have a distribution that is much more complex than the usual concept of marginal marine sediments. The chief factors that control the distribution are: (1) earlier deposition of coarse sediments at depths now below the effective reach of wave action, (2) present-day currents that by-pass fine detrital sediments and allow accumulation only of coarse calcareous organic sediments, and (3) present-day deposition of fine sands in areas adjoining beaches and of silts in deeper water. The mineralogy of the inner shelf and bank sediments is similar to that of the Pliocene-Pleistocene rocks that crop out on land and on the sea floor; hence they are considered as having been derived from Pliocene-Pleistocene rocks or from the same sources that supplied the Pliocene-Pleistocene sediments. Clastic sediments in the vicinity of Los Coronados Islands appear to be locally derived from the Miocene rocks of the islands.

INTRODUCTION

Acoustic studies conducted by the University of California Division of War Research at the United States Navy Radio and Sound Laboratory in San Diego, California, required the collection of numerous samples from the sea floor. Most of these were obtained off San Diego during the period April, 1942, to February, 1945. Because of their dense spacing, the samples yield a picture of sediment distribution that has been equaled at few other places in the world. The main suite has been supplemented by prewar and postwar samples taken in portions of the area where acoustic studies were not made.

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Altogether, 1,656 samples are available. These include 132 large dredge hauls; the remainder are smaller samples taken with snappers or scoopfish (Emery and Gould, 1948). In addition, there are 184 usable photographs of the bottom, some of which have been described earlier by Shepard and Emery (1946).

Each of the authors participated in both collection and study of the samples but made his main contribution to one phase of the work. Shepard planned and conducted the field operations and is responsible for most of the physiographic interpretation, Butcher studied the rocks, Gould investigated the minerals in the sediments, and Emery made other sediment analyses and brought the various results together into this report. Because of the very large number of samples and the comprehensive scope of the work, this was necessarily a co-operative project. The work was aided by many other persons, chief among whom are Dr. Orville L. Bandy, Mr. R. D. Briggs, Mrs. Jane Dinkens, Mrs. Anne King, and Miss Frances L. Parker. Funds for the field work and some of the laboratory studies were provided by the University of California Division of War Research. Additional laboratory studies were made possible by fellowships granted by the Allan Hancock Foundation, by the Scripps Institution of Oceanography, and by Shell Oil Company.

TOPOGRAPHY

SOURCES OF DATA

Surveys by the United States Coast and Geodetic Survey during 1934 and 1935 gave a good coverage of the nearshore area from Point Loma to the Mexican border and provided additional information along portions of the outer shelf and the slope down into San Diego Trough. Scattered soundings south of the Mexican border were available on Hydrographic Office charts. However, the needs for the acoustic work were so exacting that additional soundings were required for all except the inner and the northern portions of the area. These were obtained on the "E. W. Scripps" with an echo-sounder of the old visual flashing-light type. Since the war the surveys have been greatly augmented, and details have been added in critical areas. This recent work has been a co-operative undertaking between the United States Navy Electronics Laboratory and Scripps Institution of Oceanography. The ships involved have been the "E. W. Scripps," the "Horizon," and the Navy ships "EPCE(R) 855" and EPCE(R) 857," all of which are equipped with recording echo-sounders (pl. 1, *C*).

Positions for the surveys were obtained by horizontal sextant angles be-

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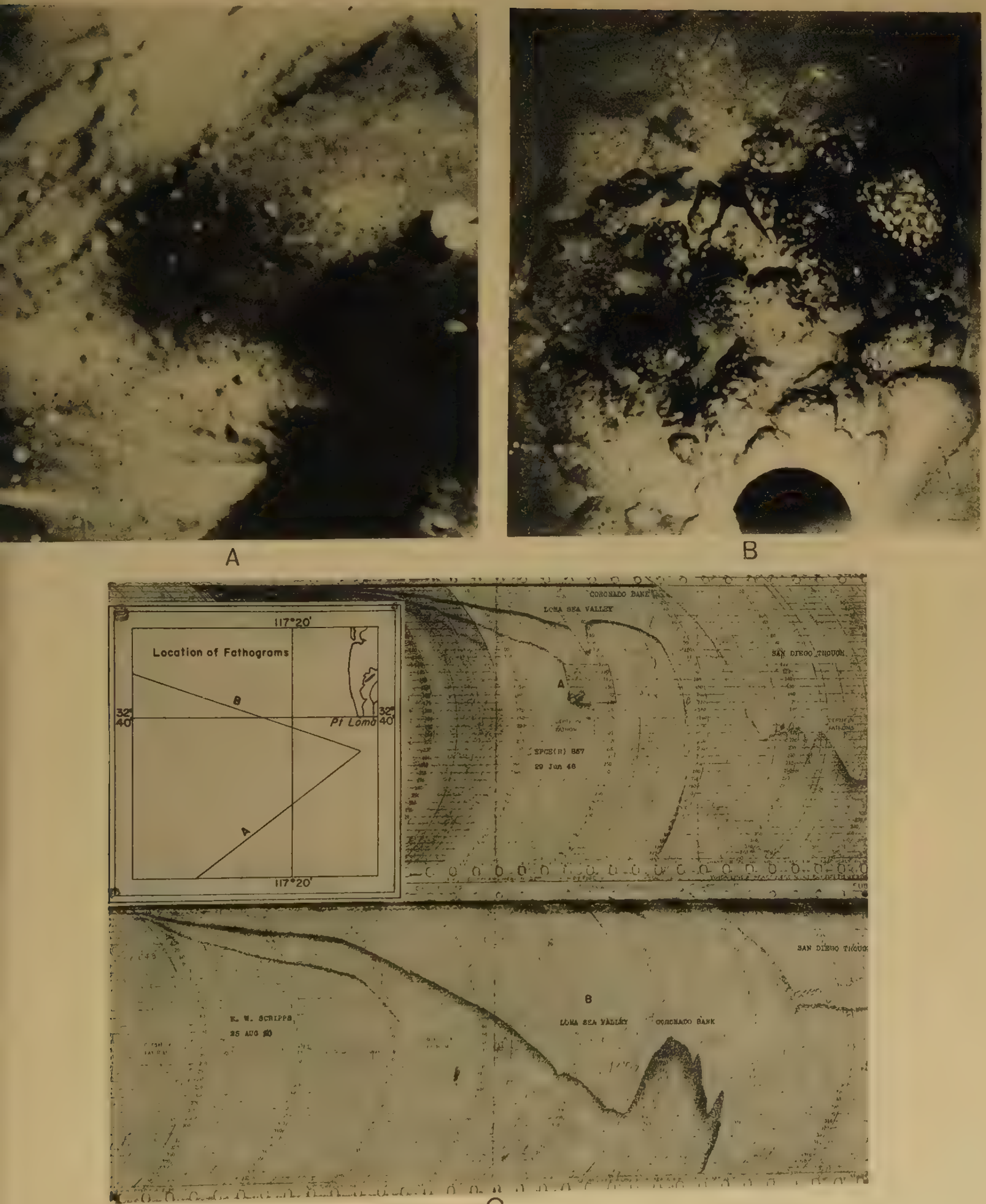
PLATE 1

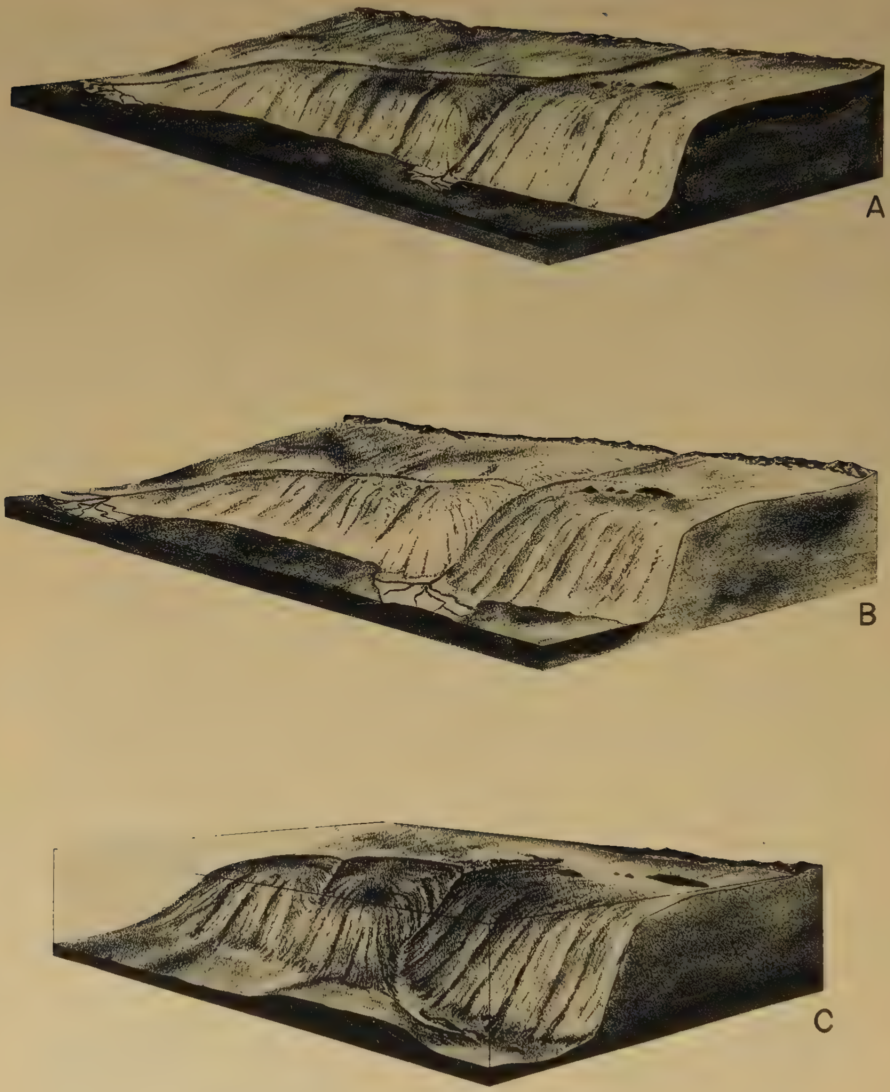
A, Underwater photograph, showing truncated edges of bedrock covered with attached organisms, mostly brachiopods. Bottom edge about 4 feet long. Lat. 32°32.′9, long. 117°20.′2, 62 fathoms. University of California Division of War Research.

B, Underwater photograph of rounded cobbles covered with attached organisms and partly buried in foraminiferal sand. Bottom edge about 4 feet long. Lat. 32°32.′5, long. 117°19.′9, 67 fathoms. University of California Division of War Research.

C, Typical fathograms off San Diego. Note the scale change on the seaward side of Coronado Bank: 400 fathoms should be added to the indicated depths in San Diego Trough.


A
B
Location of Fathograms
117°20'
32° 40'
Pt Loma
B
A
117°20'
CORONADO BANK
LOMA SEA VALLEY
SAN DIEGO TROUGH
A
EPCE(R) 857
29 Jun 48
SAN DIEGO TROUGH
B
LOMA SEA VALLEY
CORONADO BANK
E. W. SCRIPPS
25 AUG 50
C

Underwater photographs and typical fathograms



Hypothetical development of Coronado Canyon tween accurately located points on shore. In some of the outer portions of the area, where angles are small and visibility poor, parts of the sounding lines could be located only by dead reckoning. The surveys are now so complete that there is little difficulty in navigating by echo-sounding, even in dense fog.

Contours based on all the soundings were drawn at 10-fathom intervals from shore to a depth of 100 fathoms, and at 50-fathom intervals below that depth (fig. 1). These contours show that the submarine area of 760 square statute miles can be divided into several sections: shelf (45 per cent), Loma Sea Valley (10 per cent), Coronado Canyon (1 per cent), Coronado Bank (5 per cent), escarpment (11 per cent), and San Diego Trough floor (28 per cent).

SHELF

A somewhat complex shelf constitutes nearly half the area. South of latitude 32°30′ it approximates the ideal continental shelf of the world, with a gradually increasing slope from shore to the break in slope at a depth of about 70 fathoms, 10 miles at sea. The average declivity from 0 to 30 fathoms is only 0°10′10″ (18 feet per mile), whereas from 30 to 70 fathoms it is four times as steep. The smoothness of its surface is broken by Los Coronados Islands, a series of small tilted fault blocks that rise along the outer portion of the shelf, and their northward extension as a low submarine ridge.

North of latitude 32°30′ the shelf is quite different. Ranging between 5 and 10 miles in width, it is steeper and has only a slight break in slope at about 60 fathoms, somewhat shallower than farther south. Beyond that depth the bottom has an average declivity of 2°30′ (230 feet per mile) to the axis of Loma Sea Valley. Just south of Point Loma the shelf is interrupted by a relatively shallow, flattened area that is bounded on the west by a 10-fathom escarpment, the latter extending northward along Point Loma a mile out from land.

CORONADO BANK

Lying between Loma Sea Valley and San Diego Trough is a fairly flat area having depths similar to those of the outer part of the shelf. Because of its shallow depth, the area in a sense belongs to the shelf, but, because of its separation from the true shelf by the deep Loma Sea Valley and by Coronado Canyon, it is termed "Coronado Bank." Owing to its relative geomorphic isolation, this area of 37 square miles has sediment which differs markedly from that of the true shelf.

The top of the bank has two high areas, separated by a saddle. The southern high has a flattened top at a depth of about 55 fathoms and is bordered by gentle slopes except to the south, where the top is sharply trenched by Coronado Canyon. The flattened top of the northern area has an average depth of about 75 fathoms. The western edge of both parts of the bank has a break in slope varying from 80 to 90 fathoms, and the eastern edge is somewhat shoaler in most places. In the saddle between the highs, depths

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PLATE 2

A, Exposure of slope and beginning of subaerial erosion.
B, Piracy of head of Loma Sea Valley by steeper Coronado Canyon. Development of delta.
C, Rise of sea-level and dissection of delta by slumping and turbidity currents.

range down to 100 fathoms. Probably the flattening of the bank top was produced during times of lower sea-level of the Pleistocene epoch, but subsequently the surfaces must have undergone some warping.

LOMA SEA VALLEY

Loma Sea Valley is fairly straight and parallel to the general structural trend of the region. It has an asymmetrical cross section with average slopes of 2°30′ on the east and 15° on the west between the 100- and 200-fathom contours. The shallow south end of the valley is more symmetrical (pl. 1, *C*). The much faulted Middle and South Coronados Islands are directly in line with an extension of the axis of the valley. Consequently, the valley may have been eroded along a fault line, or it may be of structural origin. Landward of the shoalest portion of Coronado Bank the valley has a divide from which its axis slopes away in both directions, running directly into San Diego Trough to the north and into Coronado Canyon to the south. An erosional origin or erosional modification of the valley is suggested by its more or less continuous outward slope and by the finding of a large quantity of cobbles in a dredging along its axis.

CORONADO CANYON

One of the most interesting topographic features of the area is Coronado Canyon. It is transverse to the general structure of the region and extends landward to within 7 miles of the coast near the Tia Juana River mouth. The landward portion of the valley reaches depths as shoal as 37 fathoms, where its gently sloping walls are apparently free of rock. Farther west, the canyon has steep rocky walls and a winding course. Several tributaries join it east of the ridge formed by Coronado Bank and the northward continuation of Los Coronados Islands. In its "water gap" through the ridge the canyon has a straight course and attains its maximum depth of 340 fathoms below surroundings with side slopes as steep as 33°. Photographs (Shepard and Emery, 1946, fig. 29) show small projecting or overhanging rock layers along the upper slopes and truncated edges of tilted beds (pl. 1, *A*). West of the gap, where the floor of the canyon has a depth of about 500 fathoms, a change in character takes place (pl. 2). The axis turns south, and a trough with blunt-headed tributaries appears. In places along this outer valley the channel divides and rejoins, leaving hills in the center. Locally, the channel is flanked by low ridges similar to those that have been described by Menard and Ludwick (1951) along the outer parts of other canyons. This peculiar troughlike valley probably crosses the southern end of San Diego Trough, and it may continue into San Clemente Basin beyond. West of the point where Coronado Canyon changes character, there is a delta-like feature, into the east side of which the outer part of the valley appears to have been cut. The top of the "delta" has a relatively flat surface at about 500 fathoms that forms an arc seaward of the mouth of the main canyon.

The usual difficult problem of origin of submarine canyons exists in the San Diego area. There is, however, some important new evidence which comes from the detailed soundings along this canyon system. The relation of Loma Sea Valley to Coronado Canyon is a feature of special significance. If this portion of the sea floor had once been subject to subaerial erosion due to greater elevation in the past, it may have been possible for a stream working headward in a saddle in the outer ridge to capture another stream flowing down what is now Loma Sea Valley (pl. 2). Subsequently, the full drainage from large valleys on shore, such as the Tia Juana and San Diego rivers, could have flowed across the ridge and cut the deep "water gap" now found submerged. The delta-like surface at the mouth of the canyon could have been formed where the stream entered the sea at this level. It seems unlikely that turbidity or other types of currents on the sea floor could have produced these typical stream-erosion features; there would have been no obvious source of sediment for the turbidity currents on the outside of the ridge prior to the cutting of the gap, nor would these currents account for the horizontal top of the "delta."

The peculiar outer valley with its depressions and low bordering ridges may have been initiated by a partial collapse of the delta after submergence. Turbidity currents coming out of the rocky gorge may have flowed down a landslide depression in the delta front, producing more of a valley appearance than would have existed previously. The presence of the low ridges along the outer valley is particularly significant, because similar features exist at the sides of channels on the fore-set slopes of deltas built into Swiss lakes (Kuenen, 1950, fig. 227).

ESCARPMENT

Beyond the break at the outer edge of the shelf and the bank is a slope leading down into San Diego Trough. This is comparable to the continental slope in its relationship to the adjacent shelf but cannot be termed a true continental slope because it does not mark the boundary between the continent and the deep sea floor. The real continental slope is about 140 miles farther seaward. Between the depths of 65 fathoms and about 500 fathoms the escarpment has an average width of 2.5 miles and a declivity of 13°. On both sides of the delta the escarpment meets the floor of the San Diego Trough at about 650 fathoms.

Closely spaced echo-sounding profiles along the slope show that a series of small and somewhat discontinuous valleys cut the escarpment. The largest, near the saddle in Coronado Bank, reaches a maximum depth below surroundings of about 100 fathoms in the middle portion of the slope, but rapidly decreases in relief both up- and downslope. The other valleys are smaller, mostly less than 40 fathoms below their surroundings. It seems likely that most of these valleys extend down to the base of the escarpment (fig. 2), but they possess few tributaries and have little in common with the larger submarine canyons. Two possible origins may be considered. One is that they are the result of landslides and turbidity currents on the escarpment, and the other is that they are drowned river valleys. Since there is no evidence of rock walls, slides in the overburden may be adequate. On the other hand, if the suggested subaerial origin of Coronado Canyon is correct, other valleys should have been cut into the outer slope during emergence. Such valleys may have been maintained or reopened to some extent by landslides and turbidity currents after their submergence.

SAN DIEGO TROUGH

The area of figure 2 includes only a small portion of the San Diego Trough. The maximum depth shown is about 720 fathoms. The floor, which extends beyond the chart, is so wide and flat that it would appear to be the top of a thick fill of sediment. Seismic measurements made by Dr. R. W. Raitt (1949) show a fill of

7,000–9,000 feet above basement rocks in the part of the trough directly off San Diego, supporting this view. A series of small deeply submerged hills, located a few miles southwest of the corner of figure 2, separate the south end of the trough from the adjacent San Clemente Basin. These hills are so close together that the sediment between them cannot be very thick. Thus they probably mark the position of the sill of a former San Diego Basin that has become filled to overflowing with sediment.

WAVES AND CURRENTS

Wave turbulence that places sediment in suspension and currents that transport the suspended material are important in controlling the type and distribution of bottom materials. A very general seasonal picture of the water characteristics can be obtained from a summary of oceanographic data collected over the San Diego Trough between 1942 and 1945 and of meteorological data from Scripps Institution, located a few miles north of the area studied (fig. 3).

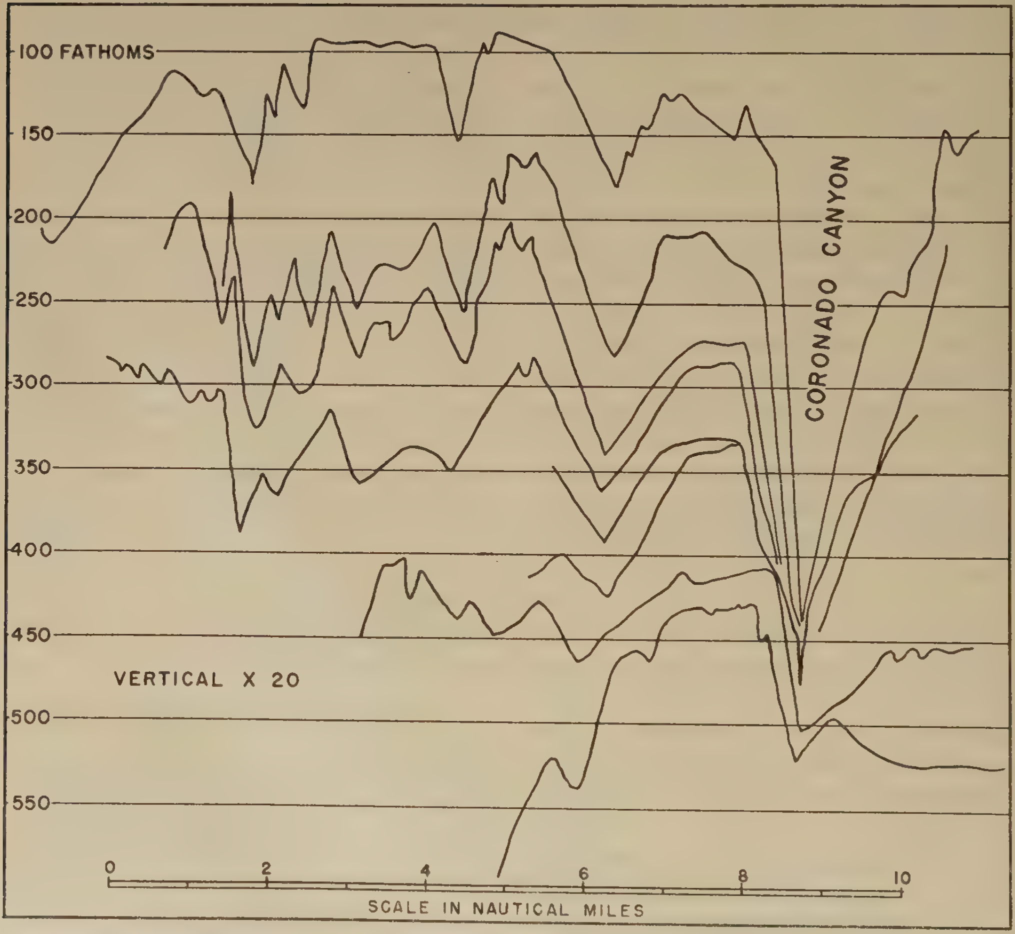


FIG. 2.—Sounding sections along face of Coronado Escarpment, showing presence of small valleys as well as of large Coronado Canyon.

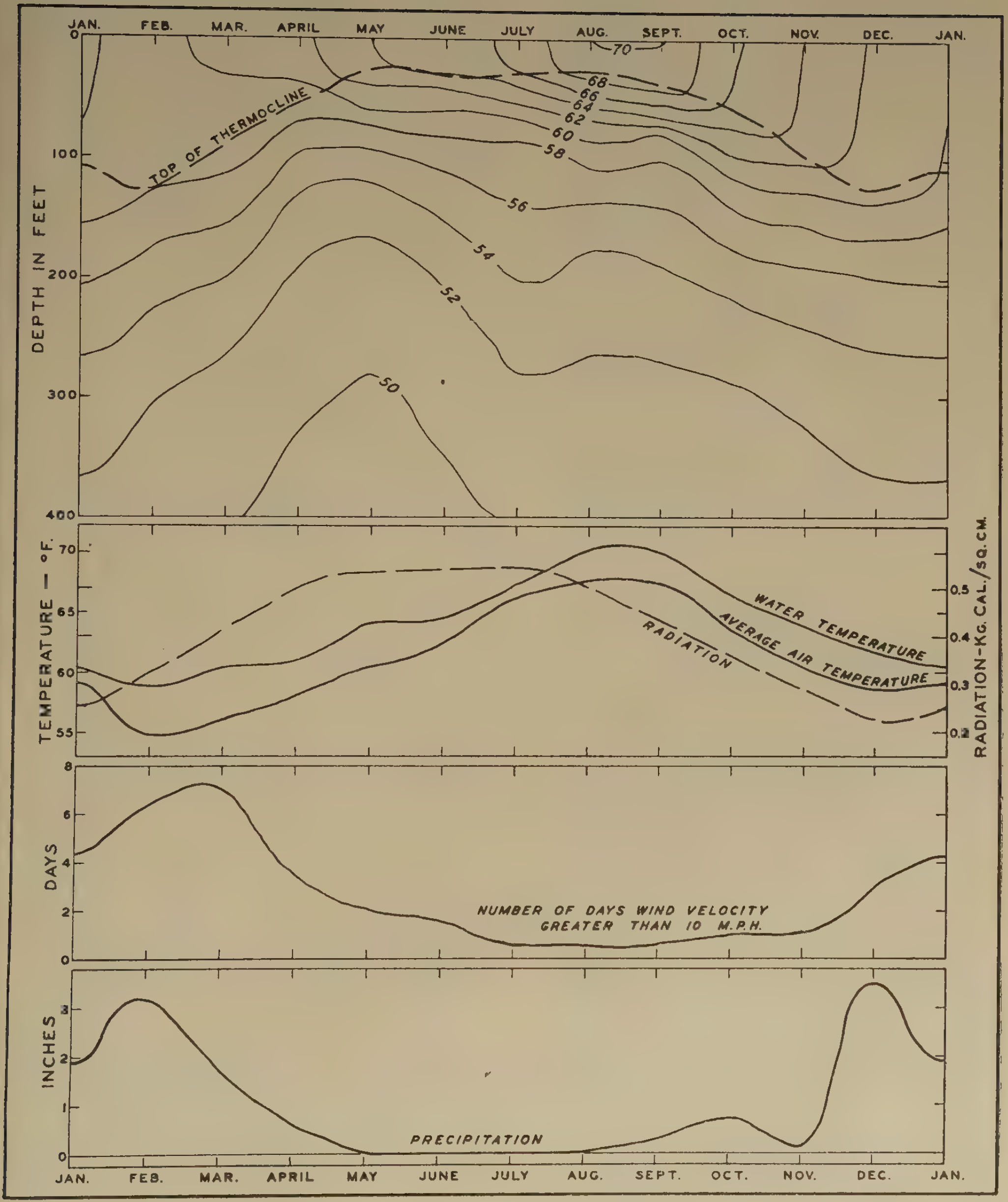


FIG. 3.—Annual variation of temperature of water and air off San Diego. Wind velocity and precipitation are also given.

Wave turbulence is a function of wind velocity, which is highest between December and April. During these months the surface water becomes well mixed to depths of more than 100 feet and cooled to about 59° F. During the summer months, when the wind is light, heating by solar radiation raises the temperature of the surface water to about 70° F., and the mixed layer is usually less than 30 feet thick; thus less disturbance of the bottom should result in summer than in winter. The months of greatest turbulence coincide with the period of annual precipitation. Streams are then intermittently active and carry to the ocean sediment which is soon redistributed by currents. Internal waves in this area have velocities of at least 0.7 knot (Ufford, 1947), but their effect on sediments is unknown because no measurements near the bottom have been made.

Currents are the main transporting agents, and, where they are of sufficiently high velocity, they produce enough turbulence to place sediment in suspension. Tidal currents usually attain their greatest velocity at narrow entrances to bays, and, accordingly, coarse sediment occurs in the entrance to San Diego Bay. Tidal currents may also be important at the outer edge of the shelf (Fleming, 1938). In addition, a general oceanic current located well offshore results from regional variations in temperature and salinity. Surveys by Sverdrup and Fleming (1941) prove that the prevailing direction of flow is southerly, and the usual quarter- to half-knot southerly set of ships on east-west courses off Point Loma shows that a fringe of this current overlaps the outer edge of the shelf. The concentration near the edge of the shelf of both the tidal and the oceanic currents is probably the chief cause of the coarsening of sediment near Los Coronados Islands and on Coronado Bank. Other currents near the shore are chiefly due to the oblique approach of waves, and these are important in controlling the distribution of sediments supplied by streams. Shepard (1950) has shown that this longshore current is predominantly southeasterly near the entrance of San Diego Bay and northerly near the mouth of the Tia Juana River.

LITHOLOGY

MAINLAND

SEDIMENTARY ROCKS

Sedimentary rocks on land range in age from Cretaceous to Pleistocene. Late Cretaceous (Chico) rocks crop out at La Jolla and Point Loma (Hanna, 1926; Hertlein and Grant, 1944) and south of the international boundary near Ensenada (Beal, 1948). In each area they consist chiefly of yellow to brown sandstone with thin beds of gray shale. Some conglomerates, rare limestones, and carbonaceous layers are included. The sandstones are characterized by an abundance of quartz and feldspar, with heavy minerals dominated by biotite and green hornblende (table 1). Glaucophane is very rare or absent. Neither micro- nor macrofossils are common in the formation as a whole.

Eocene beds resting unconformably on Cretaceous have been divided by Hanna (1926) into four members. Lowest of these is the Delmar sand, consisting of green, gray, purple, and red sands and sandy shales, with some thin beds composed almost entirely of oyster shells. The fossils are characteristic of brackish water. Next is the Torrey sand, massive, white, and probably nonmarine. The overlying Rose Canyon shale consists of light-gray mudstone, gray shale, fine sandstones, and lenses of conglomerate near the top. The sandstones range from light to dark brown and are commonly cemented by calcite. Pebbles and cobbles of the conglomerate are mostly well-rounded metavolcanic rocks. The topmost member, the Poway conglomerate, is similar to the conglomerate of the upper Rose Canyon. It includes some lenses of cross-bedded yellow and brown sands and gray shales. Much of this formation appears to be of continental origin. Lithologically, the Eocene rocks resemble those of the Cretaceous, but generally they may be distinguished by their poorer consolidation. Unlike those in the Cretaceous sands, the heavy minerals of the Eocene sands are usually high in epidote and sphene and low in biotite and green hornblende (table 1).

Oligocene rocks appear to be absent and Miocene rocks, other than the Comondu formation, are unknown on the mainland nearer than 30 miles north of San Diego and several hundred miles south of it. The Comondu formation, predominantly of Miocene age, covers a wide area south of the international boundary directly inshore from Los Coronados Islands (Beal, 1948). It is highly varied, consisting of rhyolitic, andesitic, and basaltic lava flows, agglomerates, and tuffs with some conglomerates, sandstones, clays, and limestones. North of San Diego, Miocene rocks are characterized by diatomaceous cherty shales, mudstones, and sandstones. The San Onofre breccia consists of breccias and conglomerates of amphibole schist and saussurite gabbro (Woodford, 1925). Glaucophane is the most outstanding heavy mineral of the schists.

Pliocene rocks cover a large area on land, being known as the San Diego formation in the United States (Hertlein and Grant, 1944) and as the Salada formation just across the border in Mexico (Beal, 1948). The Pliocene generally consists of poorly cemented, fine to coarse-grained, gray to brown sandstones with some shales, shell beds, marls, and conglomerates. The heavy minerals appear to be similar to those of the Eocene rocks, except that actinolite and hornblende are more abundant (table 1). Atop the widespread Linda Vista terrace is a thin capping of red and brown conglomerate and sand, known as the "Sweitzer formation" (Hertlein and Grant, 1944).

Gravels, sands, muds, and shell beds of Pleistocene age occur throughout the land portion of the area shown in figure 1. Their poor cementation permits them to be broken down easily and redeposited with modern sediments.

METAMORPHIC ROCKS

Metamorphic rocks occur within the basement complex east of San Diego and in the central area of Baja California. These rocks are considered Triassic and Jurassic in age (Hanna, 1926). The nearest are the Black Mountain series (renamed the "Santiago Peak series" by Larsen, 1948) of metamorphosed trachytic and andesitic flows, agglomerates, tuffs, with conglomerates, sandstones, and shales. Coarser schists and gneisses, possibly of Paleozoic age, occur in the high mountains farther east of San Diego. No outcrops of the Jurassic Franciscan glaucophane schists are known in the region. Irregularly altered sedimentary and igneous rocks, grouped as the San Fernando formation of Cretaceous age, crop out 100 miles southeast of San Diego.

IGNEOUS ROCKS

A large composite batholith of middle and late Cretaceous age (Woodford and Harriss, 1938) forms the core of the peninsula of Baja California and the high

TABLE 1

Mineral Composition of Rocks in the San Diego Area

Mineral Species	Mainland													Coronado Islands		Offshore			
	Pre-Tertiary Volcanics, Agglomerates, and Tonolite Batholith, East of San Diego, Calif.*	Cretaceous—La Jolla, Calif. (Av. of 4 Samples)	Cretaceous—Pt. Banda, Lower California, Mexico	Eocene—Del Mar Sand, La Jolla, Calif.	Eocene—Torrey Sand, La Jolla, Calif. (Av. of 2 Samples)	Eocene—Rose Canyon Shale, La Jolla, Calif. (Av. of 2 Samples)	Eocene—Rose Canyon Shale, near Mercy Hospital, San Diego, Calif.*	Pliocene—San Diego Fm., Pacific Beach, Calif.	Pliocene—San Diego Fm., near Mercy Hospital, San Diego, Calif.*	Pliocene—San Diego Fm., India and Upas St., San Diego, Calif.*	Pliocene—San Diego Fm., near International Boundary*	Pliocene-Pleistocene? Sweitzer Fm., Balboa Park, San Diego, Calif.*	Beaches—Southern and Lower California, Descanso to Oceanside (Av. of 6 Samples)†	Miocene—South Coronado Island (Av. of 3 Samples)	Miocene—North Coronado Island	Cretaceous—Shale, South of Point Loma	Eocene?—Sandstone, Coronado Island Area	Pliocene?—Sandstone, Coronado Bank (Av. of 4 Samples)	Pliocene?—Shale, Coronado Bank (Av. of 3 Samples)
Light minerals:																			
Quartz	X‡	...	...	...	...	...	54.9%	...	41.8%	50.5%	52.3%	50.2%	46.2%	...	...	...	...	...	...
Plagioclase	X	...	...	...	...	...	25.0	...	24.9	12.1	16.8	11.1	31.5	...	...	...	...	...	...
Orthoclase	X	...	...	...	...	...	19.0	...	29.9	25.3	19.8	35.2	22.3	...	...	...	...	...	...
Calcite	X	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Sericite	X	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Rock fragments	...	...	...	...	...	...	...	...	...	...	...	3.0	...	...	...	...	...	...	...
Heavy minerals:	...	...	...	...	...	...	1.1%	...	3.4%	12.1%	11.1%	0.5%	...	...	...	...	...	...	...
Green hornblende	X	27%	p	...	1%	10%	...	35%	A	A	A	A	74.7%	1%	p	1%	...	13%	1%
Brown hornblende	...	p‡	...	...	p	...	...	...	RR	R	R	...	...	...	...	...	...	...	...
Actinolite	...	p	1%	...	p	...	...	9	A	MA	MA	A	1.3	1	...	...	p	4	2
Magnetite	X	...	...	...	...	...	VR‡	...	R	R	R	A	2.0	...	...	...	...	...	...
Ilmenite	...	...	...	...	...	...	MA‡	...	MA	MA	MA	A	1.3	...	...	...	...	...	...
Opaque	...	4	35	27%	14	22	...	7	...	...	...	...	...	34	38%	35	23%	14	14
Barite	...	...	...	...	...	...	...	...	...	...	...	...	0.4	p	...	...	...	...	...
Hypersthene	...	p	...	...	...	p	...	...	...	...	...	...	2.3	...	...	...	...	1	...
Biotite	X	57	15	3	p	11	...	18	RR	RR	A	A	2.8	6	17	3	6	27	36

* Reported by G. A. Macdonald in Hertlein and Grant (1944).

† Reported by J. F. Gale (Master's thesis, University of Southern California).

‡ Description of symbols: "X" indicates present, but relative abundance has not been determined; "p" indicates present in amounts less than 1 per cent; "A" = abundant, "MA" = moderately abundant "RR" = rather rare, "R" = rare, "VR" = very rare.

TABLE 1—*Continued*

MINERAL SPECIES	MAINLAND													CORONADO ISLANDS		OFFSHORE			
	Pre-Tertiary Volcanics, Agglomerates, and Tonolite Batholith, East of San Diego, Calif.*	Cretaceous—La Jolla, Calif. (Av. of 4 Samples)	Cretaceous—Pt. Banda, Lower California, Mexico	Eocene—Del Mar Sand, La Jolla, Calif.	Eocene—Torrey Sand, La Jolla, Calif. (Av. of 2 Samples)	Eocene—Rose Canyon Shale, La Jolla, Calif. (Av. of 2 Samples)	Eocene—Rose Canyon Shale, near Mercy Hospital, San Diego, Calif.*	Pliocene—San Diego Fm., Pacific Beach, Calif.	Pliocene—San Diego Fm., near Mercy Hospital, San Diego, Calif.*	Pliocene—San Diego Fm., India and Upas St., San Diego, Calif.*	Pliocene—San Diego Fm., near International Boundary*	Pliocene-Pleistocene? Sweitzer Fm., Balboa Park, San Diego, Calif.*	Beaches—Southern and Lower California, Descanso to Oceanside (Av. of 6 Samples)†	Miocene—South Coronado Island (Av. of 3 Samples)	Miocene—North Coronado Island	Cretaceous—Shale, South of Point Loma	Eocene?—Sandstone, Coronado Island Area	Pliocene?—Sandstone, Coronado Bank (Av. of 4 Samples)	Pliocene?—Shale, Coronado Bank (Av. of 3 Samples)
Heavy minerals—(Continued):																			
Epidote	X	2%	15%	31%	36%	9%	A‡	7%	MA	RR	RR	A	0.6%	12%	12%	p	p	2%	1%
Zoisite		p			p	1	A		MA	RR	RR	RR	0.7	p					
Garnet		2	1	3	3	1	RR‡	6	MA	R	R	RR		3	1		5%	1	p
Sphene	X	3	8	6	13	11	RR	8	MA	MA	MA	R	1.3	8	1	p	11	3	p
Apatite	X	p	p			1								p			2	p	p
Leucoxene													0.4						
Chlorite	X	2	1	15		20							0.2	2	20	1%	2	20	19
Basalt. hb.													0.5						
Zircon	X	1	3	1	4	3	R‡	1	MA	MA	MA	MA			p	p	4	2	p
Glaucophane						p			RR	R		MA	0.3	p				p	p
Olivine													1.3						
Enstatite													1.1						
Hematite													0.2						
Limonite	X																		
Alteration		1	19	13	28	10		8					4.8	31	9	58	45	11	24
Augite	X											MA	0.8						
Diopside	X												0.2						
Rutile		p			p					R	R	RR	0.1						
Andalusite		p					R												
Pyrite	X												0.3						
Uralite	X																		
Piedmontite							RR												
Tourmaline				1		p		p				R	0.8	p					
Topaz													0.6						
Collophane													1.0						
Clinozoisite																			p
Unknown		p			p														

country east of San Diego. Individual intrusive units range in composition from gabbro to granite with tonolite, gabbro, and granodiorite being especially widespread. A typical tonolite consists of andesine, quartz, biotite, and hornblende, with sphene, zircon, magnetite, and apatite as accessory minerals.

Aplite and pegmatite dikes cut the batholith and associated metamorphic rocks. These contain various semiprecious gem minerals, such as tourmaline, spodumene, and beryl. Postbatholithic rocks are limited to a few mafic dikes and andesite plugs.

Cenozoic volcanic rocks have been described with the Comondu formation.

LOS CORONADOS ISLANDS

The various authors of this report visited the islands five times between 1935 and 1951. Although the geological study is not yet complete, some of the new information should be presented here. Formation thicknesses are based entirely upon estimates.

Strata of each of the three islands of the Los Coronados group strike almost due north and dip about 25° to the west. Little has been learned of the structural relations of the islands because of the large submerged areas between them; however, faults with throws of several hundred feet occur on Middle and South Islands.

North Island consists of about 500 feet of red to reddish-brown, medium- to coarse-grained sandstone in beds ranging from a few inches to a few feet in thickness. A mineral analysis of three sandstone samples is presented in table 1. Pebbles occur in the lower sandstones but are not common.

Middle Rock is composed of about 125 feet of red to reddish-brown conglomerate, having a sandstone matrix and containing sandstone beds up to 5 feet thick. The sandstone is like that of North Island. Cobbles and boulders of the conglomerate vary between 2 inches and 2 feet in diameter and are chiefly of rounded metavolcanic rocks, schist, and quartzite.

Middle Island is the most complex of the group. The central and eastern part consists of about 50 feet of red conglomerate and sandstone like that of Middle Rock, overlain by about 200 feet of light-green conglomerate and coarse sandstone. The green conglomerate consists of pebbles, cobbles, and boulders of volcanic and metamorphic rocks, including glaucophane schist and others of the Franciscan type. On the northwestern and southwestern sides of the main Middle Island, red conglomerate is in fault contact with the green rocks. A maximum thickness of about 100 feet of the red conglomerate was observed. In each area drag against the fault plane indicates relative upward movement of the red rocks. Thus at least some of the red rocks are older than some of the green ones. An islet east of the main Middle Island, which is separated only at high tide, consists entirely of a third kind of rock, a gray, mildly altered andesite or basalt breccia. The angular clastics range up to 6 feet in diameter. A thickness of about 75 feet of the formation is exposed.

South Island, the largest of the group, consists chiefly of green conglomerate and sandstone like that of Middle Island. A mineral analysis of the sandstone and matrix is presented in table 1. The total thickness appears to be about 700 feet. In the northeastern portion of the island the green conglomerate and sandstone rest upon 120 feet of sandy shales, from which a few Foraminifera were recovered. In fault contact with the sandy shales is a section of shaly sandstone about 150 feet thick that has moved upward in relative position and may be the lower part of the same formation. This sandstone, in turn, rests upon about 100 feet of green conglomerate and sandstone lithologically like the main formation of the island. The two deep coves on opposite sides of the island are cut in altered volcanic breccia like that of the islet east of Middle Island. In both coves this rock has a thickness of about 125 feet and is overlain by 50–100 feet of sandy shale. The breccia and shale form a fault block that trends across the island and has probably moved upward in the section; thus the breccia is probably the oldest exposed rock of South Island, but its age relation to the red conglomerate and sandstone of Middle and North Islands is unknown.

After a visit to the islands in 1922, Woodford tentatively assigned the green conglomerate of South and Middle Islands to the San Onofre breccia of Miocene age on the basis of its lithology (Woodford, 1925, pp. 182, 183; Beal, 1948, pp. 24, 25). No macrofossils have been discovered in any of the rocks, but we found some Foraminifera in the sandy shale and shaly sandstone in the northeastern part of South Island. They consist entirely of limonitic internal casts, possibly originally of pyrite. Dr. Orville Bandy, of the University of Southern California, identified the following forms: *Bolivina marginata* Cushman, *Buliminella subfusiformis* Cushman, *Nonion costiferus* (Cushman), *Nonionella miocenica* Cushman, (?) *Siphogenerina* sp. (partial internal mold), *Valvulineria* cf. *miocenica* Cushman. These Foraminifera are characteristic of the middle Miocene, supporting the lithologic correlation of the overlying and probably also underlying green conglomerate with the San Onofre breccia.

OFFSHORE

INTRODUCTION

A total of 450 samples containing rocks have been recovered from the offshore area. They can be divided into three classes: bedrock essentially in place, transported rocks, and authigenic rocks. Those essentially in place were distinguished on the basis of angularity, similarity in composition, and fragility (Emery and Shepard, 1945). Hard igneous and metamorphic rocks require much more transportation to become rounded than do friable sandstones, so the former were considered transported, whereas very friable subangular to subround sedimentary rocks were included with the rocks essentially in place. Adjacent samples should show a consistent relationship to each other; a fragment aberrant to the rest of the group is not likely to be in place. Authigenic rocks are confined to phosphorite in its various forms. Detailed descriptions of each sample are not included in this report but are available to the interested reader in a doctoral thesis on the lithology of the area (Butcher, 1951).

ROCKS ESSENTIALLY IN PLACE

General.—Rocks essentially in place occur in three areas of the chart. Two of the areas, near the edge of the shelf, are separated by Coronado Canyon at the 32°30′ parallel of latitude. These are the Coronado Bank area and Los Coronados Islands area. The third area of outcrops extends south from Point Loma for about 5 miles. Table 2 lists the number of samples containing rocks believed to be essentially in place, and figure 4 is a chart showing the distribution of the main types of bedrock.

Coronado Bank.—Proof of the existence of outcrops in the Coronado Bank-

Coronado Escarpment area is obtained from underwater photographs of the bottom. One picture (pl. 1, *A*) reveals the truncated edges of sedimentary beds that form small hogbacks. Dredgings show that the rocks of the bank consist mostly of sandstone and shale (table 2). The sandstones are prevailingly light gray or tan, and in places greenish. Most are fine-grained but some are medium- and coarse-grained; they range from well cemented to poorly cemented and friable. Calcite is generally only a minor constituent, but some beds are cemented with this mineral, and calcareous fossils are not uncommon. Less commonly, limonite serves as the cementing material. The sand grains are mostly angular to subangular and are composed of quartz and feldspar with occasional rock fragments. Biotite is an abundant accessory mineral in some rocks. Many sandstones are silty.

TABLE 2

NUMBER OF SAMPLES CONTAINING ROCKS ESSENTIALLY IN PLACE, CLASSIFIED BY AREA AND TYPE

Rock Type	Coronado Bank	Los Coronados Islands Area	Point Loma Area
Total samples	66	8	44
Sandstone	29	7	15
Shale	40	4	36
Limestone	9	....	....
Conglomerate	3	....	....

The shales are light gray, light brown, or occasionally greenish gray. Most of them are soft and sandy or silty, but some are black and hard. Calcareous bands and joint fillings occur in some fragments, and fossils are sparse.

White shelly marl, present in small amounts, is rendered friable by abundant silt and sand. Its color ranges from light gray to light brown, depending on the amount of clastic material. The preservation of fossils in the marl is poor; though some Foraminifera, ostracods, echinoid spines and plates, and small corals were found.

A few samples consist of a reddish-brown, poorly sorted conglomerate with round to subround pebbles set in a matrix of angular sand grains. The pebbles are of the metamorphic, intrusive, and volcanic types found in the basement complex to the east. Similar conglomerates probably supplied some of the metamorphic and igneous pebbles that had to be classed as transported because none of the conglomerate matrix remained on them.

Four samples are distinctive enough to warrant separate description. One is a finely laminated, calcareous gray shale, partly weathered to a light brown. The individual laminae are less than 1 mm. thick. Two other samples are of dark-gray shale containing some white, fine-grained sand. The sand is friable and occurs in much distorted beds and even as separate lumps. Possibly it is similar to some of the modern lenses from the deep floor of San Diego Trough described by Ludwick (1950). Lastly, a sample of brown, calcareous, silty sandstone contains two internal casts of a pelecypod identified by Dr. W. H. Popenoe, of the University of California at Los Angeles, as *Thyasira*, which ranges from Oligocene to Recent but is commonest in Pliocene strata.

Foraminifera have been obtained from 13 of the rock samples from the bank. Eleven contain forms which, according to Miss Frances L. Parker, of Scripps Institution, and Dr. Orville Bandy, range from late Pliocene to Recent. These are as follows: *Cassidulina delicata* Cushman, *C. limbata* Cushman and Hughes, *C. tortuosa* Cushman and Hughes, *Bolivina acuminata* Natland, *B. argentea* Cushman, *B. spissa* Cushman, *Uvigerina peregrina* Cushman, *Cibicides fletcheri* Galloway and Wissler, *Rupertia stabilis* Wallich.

If fossiliferous Miocene or Eocene rocks had been eroded to form the bank, reworked Miocene or Eocene Foraminifera might be expected in the unconsolidated sediments. A detailed study of the Foraminifera in 78 sediment samples from the bank showed no forms that do not occur in late Pliocene to Recent formations. Supporting evidence for that age has been obtained from heavy-mineral counts (table 1) on four rock samples. These have appreciable amounts of biotite and actinolite, minerals that have a common association only in the Pliocene to Recent sedimentary rocks of this area (table 1). Glaucophane is present to a limited extent but probably indicates only Miocene or later age.

The minimum age of the rocks would appear to be late Pleistocene, because they are truncated by flat surfaces believed to have been cut by wave action during times of lowered sea-level of the glacial epochs. This physiographic evidence is supplemented by the finding in two sediment samples of shell fragments that have been identified by Dr. Popenoe as not older than Pleistocene. One shell, *Venerupia kennerleyi* (Reeve), is a coldwater form not now known south of latitude 37°. Possibly it lived on the bank during a glacial stage of shallower and colder water.

The San Diego and Sweitzer formations on the adjacent land are also of late Pliocene to Pleistocene age, and, in general, the rocks of the two areas are remarkably similar. The sandstones and conglomerates have the same color in each area, and shell beds are present in both. The formations of the two areas differ in the greater amount of shale and the finer grain size of the sandstones on the bank, but this may have resulted from the greater distance of the present bank area from the shoreline of San Diego–Sweitzer time.

The wide distribution of the samples containing post-late Pliocene fossils and the absence of reworked older fossils indicates that the late Pliocene to late Pleistocene rocks form a continuous blanket of unknown thickness over the bank.

Los Coronados Islands area.—A total of eleven samples, some probably in place, were taken just south of Coronado Canyon and around Los Coronados Islands. Two of these, on the south wall of Coronado Canyon, include large angular pieces of sandstone and shale. The sandstone is yellow to red and coarse-grained. Most of it is lithologically like that on South Island. Two samples from southeast of South Island contain gray, green, and brown fine- to coarse-grained sandstone, which is also similar to rocks of South Island. Two samples from near the south end of North Island are reddish brown and fine-grained, resembling the sandstones of that island. One other, from south of North Island, is light brown, fine-grained, and arkosic, like the sandstone of Middle Island. North of North Island, dredgings produced angular fragments of hard gray shale, grading into a gray, fine-grained silty sandstone. None of these samples is fossiliferous, so their age is not known, but lithologic similarity indicates that they are of the same age as the island rocks.

One sample from the edge of the shelf is a serpentine with slickensides. Although such a rock might be expected along a fault, this sample is probably not in place.

The rocks of the islands have an approximate north strike and a west dip; thus they would lie beneath, and be older than, the rocks of Coronado Bank if there were no intervening faulting or change in strike. No rocks observed on or around the islands resembled those of the bank. Outcrops near the islands should thus be of pre-late Pliocene age. The close resemblance in composition, texture, and color of the Miocene rocks of the islands and those from the surrounding sea floor indicates that the latter are also of Miocene age.

TABLE 3

NUMBER OF SAMPLES CONTAINING TRANSPORTED ROCKS, CLASSIFIED BY AREA AND TYPE

Rock Type	Coronado Bank	Los Coronados Islands Area	Point Loma Area	Tia Juana River Area
Total samples	104	46	76	19
Sandstone	25	14	17	4
Shale	13	1	19	2
Limestone	2	......	......	......
Conglomerate	1	......	......	2
Volcanics	59	30	42	16
Intrusives	11	10	11	5
Metamorphics	22	17	15	8

Point Loma area.—The outcrop area extending southerly from Point Loma consists mostly of shale with a small amount of sandstone, as indicated in table 2. The shale is distinctive: gray to light gray and soft, with a few flakes of biotite. Carbonaceous fragments are quite generally present, and one sample contained a small piece of coal. The shale at this area, unlike the other shales from the sea floor, has a greasy smear when scratched with a knife. The same characteristic is found in some Point Loma shales. It indicates plasticity resulting from a high clay content. Fine-grained, light-gray to grayish-brown, silty, friable sandstones with some biotite are also present in the submarine outcrops. Some of these sandstones are arkosic. Limonitic staining is occasionally present, and greenish staining is less frequent. All these characteristics are similar to those of the Cretaceous Chico formation that crops out on land at the near-by tip of Point Loma.

A heavy-mineral analysis of one of the shales is not very definitive, possibly because of extensive alteration by weathering. Though rare, a few Foraminifera have been recovered from the shale. Dr. O. L. Bandy, of the University of Southern California, identified two species as *Anomolina* sp. and *Cribrostomoides cretacea* aff. Cushman and Goudkoff, which are late Cretaceous in age. The latter is identical with a form found in the Point Loma Cretaceous. Correlation of the submarine outcrops with the Chico of Point Loma is evident.

TRANSPORTED ROCKS

Rock types.—Many of the samples with fragments from outcrops also contained pieces of a transported character. Other samples, however, had transported pieces alone, largely well-rounded metamorphic quartzites and volcanic rocks. Some pebbles of sandstone, shale, limestone, conglomerate, and intrusive rocks were also present. Table 3 lists the transported samples according to their gross lithology. Figure 5 shows that most of the transported rocks occur in the same areas that have outcrops: the Coronado Bank, Los Coronados Islands, and the Point Loma areas. There is an additional large area of transported samples near the coast off the Tia Juana River mouth, a smaller area farther north along Coronado Strand, and a still smaller one in the entrance to San Diego Bay. Some transported rocks also occur along the axis of Loma Sea Valley.

Sources.—The transported rocks of the submarine section must have been derived from outcrops in the area, from present or past land areas, or from some combination of both. Metamorphic, intrusive, or volcanic rocks occur in 65–80 per cent of the samples in each area. The remainder of the samples consists only of sedimentary rocks. If the transported rocks were derived entirely from near-by outcrops, the lithologic types should be similar to those of the bedrock, but not exactly in the same ratios because of differences in hardness, the more easily abraded rocks undergoing the greater loss during transportation. For example, sandstone and shale occur in a ratio of 3 to 4 in the bedrock of the Coronado Bank area, and in the transported rocks of the same area they occur in a ratio of 2 to 1. In the bedrock of the Point Loma area, shale is more than twice as abundant as sandstone, and in the transported rocks of the same area shale and sandstone are about equal.

Had the transported materials been derived from a distant source and the distributing agencies acted over the whole area, the same ratios of lithologic types should exist over the whole area. Thus derivation from the east and redistribution by waves or streams should produce a uniformity of composition in the transported materials. Table 3 shows that the volcanic, intrusive, and metamorphic rocks do have a nearly constant ratio to one another. If these rocks were derived only from local sources, none should occur in the Point Loma area, where there are no conglomerates in the submarine section to provide the crystalline rocks. It seems probable that most of the volcanic, metamorphic, and intrusive rocks have been derived from distant sources and spread over the entire area by stream or marine agencies.

The large area of rounded cobbles and boulders off the Tia Juana River is noteworthy for an almost complete lack of fine sediment cover and for the absence of bedrock. The rounded rocks from that area are almost exclusively of intrusive, metamorphic, and volcanic types. Encrustations on the rocks show that they are not now being moved about. Probably they were deposited by the river sometime in the past. The rock types in this area may well be indicative of the kinds that were transported from land and deposited with locally derived rocks in the other areas of the sea floor. The boulder area off Coronado Strand farther north may be of a different origin because of the predominance in it of sedimentary rocks, though possibly the latter were added by kelp-rafting of rocks from the up-current Point Loma area, where kelp is abundant. Gravel in the entrance of San Diego Bay may be ballast that was dumped by sailing ships during the last century. This is said to be the origin of the near-by Ballast Point.

If gravels were deposited atop bedrock over the whole shelf and bank, subsequent deposition of sands and finer sediments has buried them except where currents are strong enough to by-pass the fine-grained sediments, leaving the bedrock and scattered gravels uncovered. The Coronado Bank and Los Coronados Islands areas lie at the edge of the shelf, where tidal and other currents are accentuated. The area of rock and cobbles extending southerly from Point Loma probably results from strong coastal currents, driven by northwesterly winds and leaving the coast at the tip of Point Loma. In addition, cobbles unrelated to bedrock occur in the entrance to San

Diego Bay, where tidal currents keep them exposed, and in two other areas near the coast and farther south. No explanation for lack of burial of the latter areas can be given.

Date of deposition.—Several lines of evidence suggest that the gravels were deposited during one of the glacial times of lowered sea-level. The bedrock on which they rest contains late Pliocene to Recent fossils, and the gravels are, of course, younger than the rock. Because the boulders rest on the flattened 55-fathom surface of Coronado Bank, they must have been deposited after or during the formation of that surface. Flint (1949, p. 435) speculated that benching at such a depth may have occurred during the last glacial lowering of sea-level. One sample contains a 56-cm. limestone boulder, and another a 36-cm. andesite boulder. These sizes are probably too large for kelp-rafting, and, so far as can be determined, bottom currents are not strong enough at the present time either to transport the cobbles and boulders or to erode the bedrock to provide materials of local derivation. Abundant encrusting organisms on the exposed surfaces show not only that the gravels are not being moved now but also that effective scour by interstitial sand does not occur. Currents sufficiently strong for such transport or erosion probably have not occurred since the period of relatively lowered sea-level during the last glacial stage. Dietz and Menard (1951) have pointed out that active erosion of the sea bottom by waves is restricted to depths of less than about 5 fathoms and that most of the area of continental shelves is now a deeply submerged remnant of marine erosion during times of glacially lowered sea-level. This conclusion appears to be supported by the great abundance of empty pholad borings in the rocks. Ricketts and Calvin (1948, p. 178) state that, although the ecology of pholads is imperfectly known, they are apparently limited in their greatest abundance to the intertidal zone, though occasionally occurring in dredged rocks as deep as 30 fathoms. The abundance of the borings suggests that they were made at a time of lowered sea-level and that the rocks have subsequently remained undisturbed. Coarse terrace deposits also characterize the Pleistocene formations on land; hence transported materials were evidently spread over the whole area during the Pleistocene epoch.

AUTHIGENIC ROCKS, PHOSPHORITE

Characteristics.—The only authigenic rock is phosphorite. This was found in 83 samples from Coronado Bank and in only 8 samples from other areas. Figure 6 shows the distribution of these samples.

The phosphorite ranges in size from a few millimeters to 43 cm. Much of it is nodular and polished as though in the process of formation. Most of the phosphorite contains the usual irregular layers that indicate discontinuous growth, but some is aphanitic and structureless. Broken and re-cemented pieces occur occasionally, and several nodular specimens include pebbles of clastic material. Some phosphatic particles contain so many silt and sand grains that they are difficult to distinguish from nonphosphatic rocks. Films of phosphorite also coat many of the other rocks of the bank, so that rocks must be broken open to determine their composition.

Fossils are not rare but are difficult to separate for identification. Borings in the phosphorite are filled with modern sediments and Foraminifera. Light-brown material is present on the outer parts of the nodules, as mentioned by Dietz, Emery, and Shepard (1942, p. 827), and dark-brown to black phosphorite generally occurs in the center of the nodules or as fragments cemented together by the lighter-brown phosphorite. The Foraminifera from these two types of phosphorite seem to show no difference in age, unlike the phosphorite dredged elsewhere off southern California. Foraminifera have been obtained from six samples. Dr. Orville Bandy identified the following forms: *Cassidulina limbata* Cushman and Hughes, *C. tortuosa* Cushman and Hughes, *C. cf. californica* Cushman and Hughes, *Cibicides fletcheri* Galloway and Wissler, *Rupertia stabilis* Wallich. This fauna is similar to that obtained from the underlying rocks, except for the absence of *Bolivina* and *Uvigerina* in the phosphorite. Reference to Natland's (1933) chart of the temperature and depth distribution of Foraminifera off California suggests that the Foraminifera of the phosphorite are characteristic of slightly shallower depth (his zone III, 125–900 feet) or slightly younger age than those of the underlying rock. In addition, two of the phosphorite nodules include a poorly preserved foraminiferal fauna possibly of Miocene age, including *Cassidulina crassa* d'Orbigny, mixed with late Pliocene to Recent species. They may well have been redeposited from Miocene rocks of Los Coronados Islands.

In situ origin.—The deposition *in situ* suggested by Dietz, Emery, and Shepard (1942) is borne out in the examination of the samples of this area by (1) the lack of abrasional rounding, (2) the fresh nodular appearance of most of the surfaces, (3) the phosphatic coatings on many boulders, and (4) the included sediment, which is of the same type as that which surrounds the nodules. Some nodules show an irregular concentric layering of phosphate and thin manganese oxide. In these nodules the direction of major growth is toward the side covered with living organisms, indicating growth in the present position. Deposition *in situ* is also suggested by the localization of the deposit; transportation with other rocks should have left deposits in other parts of the sea floor. Furthermore, no phosphorite has been reported in the rocks exposed on the near-by land. The mode of formation is apparently by chemical precipitation, although proof of this rests on further investigation of the physical-chemical properties of sea water with respect to phosphate deposition.

Date of deposition.—Dietz, Emery, and Shepard (1942) suggested that the phosphorite off southern California is largely Pliocene or Quaternary in age, though Miocene Foraminifera were most commonly included. Later, Emery and Dietz (1950) gave evidence for a Miocene age for the bulk of the phosphorite. A Quaternary age is indicated for the phosphorite off San Diego because of the enclosed Foraminifera and the stratigraphic relations. The phosphorite rests in part upon a surface of the bank that ranges from 75 to 90 fathoms in depth and has a slope to the north and west from the shallow southern end of the bank. If the phosphorite were formed *in situ*, it must be younger than this surface. Because the rocks forming the surface are late Pliocene at the oldest, the phosphorite must be younger than late Pliocene. The surface at about 55 fathoms of presumably late glacial age has practically no phosphorite nodules. Only one nodule was found within the 60-fathom contour of figure 1. Therefore, most of the phosphorite appears to be older than the last glacial stage and, thus, is pre-late Pleistocene. A similar relationship exists at Fortymile Bank farther offshore (Emery and Dietz, 1950).

Eight samples containing phosphorite

were obtained outside the bank area. One was found off Point Loma, where the water is shallower and the sediment less fossiliferous than on the bank. One came from the east side of Loma Sea Valley near Coronado Bank. The remaining six samples are from the area surrounding Los Coronados Islands. The environment of these latter samples is similar to that of the bank, for both the depths and the sediments are comparable. The phosphorite of three of these samples replaces shells, none of which are larger than 5 cm. Possibly they represent a later deposition of phosphorite than the large nodules of Coronado Bank and can be correlated with the coatings found on other kinds of rock.

UNCONSOLIDATED SEDIMENTS

GENERAL

Knowledge of the unconsolidated sediments is based on a study of more than thirteen hundred samples from all parts of the submarine area. The coarse unconsolidated materials, such as granules, pebbles, cobbles, and boulders, have been discussed in the section on lithology, because of their close association with the underlying bedrock. There is reason to believe that some of the sediments constituting the surface layer were laid down when the sea-level was relatively lower than now and are consequently older than the materials now being deposited. Since definite age determinations are lacking, however, we have included all the finer surficial materials in the discussion of unconsolidated sediments.

Classified according to composition, the modern sediments fall into three broad groups: (1) clastic sediments, (2) calcareous organic sediments, and (3) mixed clastic and calcareous organic sediments. Strictly speaking, neither the clastic nor the organic sediments are wholly of clastic or organic origin. However, the clastic sediments consist predominantly of detrital materials and the organic sediments predominantly of calcareous organisms. The third group, mixed clastic and calcareous organic sediments, contains approximately equal amounts of the two main types. Of these three broad groups, the sediments of clastic origin are by far the most widespread, covering 685 square statute miles, approximately 90 per cent of the whole submarine area. In contrast, the calcareous organic sediments make up only 8 per cent, or 68 square miles. Least abundant are the mixed sediments, which cover only 2 per cent, or 15 square miles.

These three major sediment groups have been further subdivided on the basis of texture and color. Altogether, 13 sediment types have been distinguished. Of this number, 9 are clastic sediments, 3 are calcareous organic sediments, and 1 is of mixed origin. The areas covered by each type of sediment are shown in chart form in figure 7. In the areas of bedrock and gravels, indicated by shading, sediment forms patches on the rock and lies between the boulders and cobbles.

AREAL DISTRIBUTION AND DESCRIPTION OF SEDIMENT TYPES

CLASTIC SEDIMENTS

Clastic sediments cover most of the shelf and all the area of the submarine slopes and valley floors. These sediments can be subdivided into five major types and four minor ones (fig. 7).

Medium to coarse gray sand.—The sediment consists of medium to coarse, light to medium olive-gray sand at Imperial Beach, in two isolated patches east and north of South Coronado Island, and in a large area off the mouth of the Tia Juana River and the Mexican coast. The area of sand off the Mexican coast may be less extensive than is shown in figure 7, because few samples are available there. The sand of Imperial Beach and the sand of the two isolated patches have a salt-and-pepper appearance and are slightly lighter in color than that off the river and the Mexican coast. This difference results from a gray coating on the sand grains in the latter area. The grains in all these areas are predominantly angular to subangular.

Medium to coarse brown sand.—A large area of medium to coarse light-reddish-brown sand occurs west of the medium to coarse gray sand and approximately in line with the Tia Juana River. The sand in this zone is notably coarser along its western boundary than elsewhere. Brown sand also was found in two small isolated patches at the outer edge of the large area of medium to coarse gray sand and in an elongate patch just south of Point Loma. Reddish sand, possibly the same as the submarine brown sand, occurs in some well borings near the mouth of the Tia Juana River. The brown sand may once have formed a practically continuous layer from Point Loma on the north to its present southern boundary at latitude 32°25′, the present discontinuity resulting from partial burial beneath medium to coarse gray sand and fine gray sand.

The brown and gray sands are remarkably similar in grain size, shape, and mineralogy. Grains of the brown sand are stained with yellow and red iron oxides. Ferric iron in the stain, determined for 3 samples of coarse brown sand, averages 0.41 per cent, and for 3 samples of coarse gray sand, only 0.25 per cent. Qualitative tests for ferrous iron were negative or weak.

Fine gray sand.—The most widespread of the clastic sediments on the shelf is a fine, light-olive-gray sand (fig. 7), which generally does not extend seaward of the 40-fathom contour. This sand is separated into a northern and a southern zone by a discontinuous arc of other bottom materials between the Tia Juana River and Point Loma. A narrow fringe of the fine gray sand also occurs along the western boundaries of the main brown-sand area and of the shell and gravel area west of Point Loma.

The northern fine-gray-sand zone consists chiefly of fine and very fine sand. The beach presents a gradation from medium and coarse sand at Imperial Beach to predominantly fine sand along Coronado Strand. This beach sand has a salt-and-pepper appearance and is slightly lighter in color than the submarine sand. Near shore the principal constituent is fine sand with minor amounts of medium sand. To the south and west there is a gradation into very fine sand with an appreciable quantity of silt. Samples along the southern and western margins of the zone show some mixture of the fine gray sand with the bordering coarse brown and gray sands.

The sediment of the southern fine-gray-sand zone consists predominantly of fine sand, with a considerably larger proportion of medium sand than is present in the northern zone. It is also noticeably lighter in color than the sand of the northern zone, and it has a salt-and-pepper appearance like the beach sand from Coronado Strand and the medium and coarse gray sand on the shelf east of Los Coronados Islands.

The fringe of fine gray sand along the western border of the main area of coarse brown sand and the area of shell and gravel farther north consists primarily of very fine sand with appreciable amounts of silt. Westward it grades within a short distance into the sand-silt area. The grains of the fine gray sand are predominantly angular to subangular.

Gray sand-silt.—The sediments of the outer edge of the shelf and the upper portions of the submarine slopes bounding San Diego Trough, Loma Sea Valley, and Coronado Canyon contain approximately equal proportions of very fine light-olive-gray sand and silt. Only a minor amount of clay is present. This sand-silt zone extends shoreward of the 30-fathom contour only south of Los Coronados Islands, but it reaches 250 fathoms in Coronado Canyon. In the Coronado Bank area, the sand-silt forms a narrow fringe surrounding the shallower calcareous organic sediments, and in turn the sand-silt grades into the silt of deeper water.

Coprolites are common constituents of the sand-silt, and the tests of Foraminifera and fragments of mollusks and other organisms are fairly abundant. Most of the detrital grains are angular, and many are coated with a light-green to grayish-brown stain.

Gray silt.—In the deeper parts of the offshore area (Loma Sea Valley and San Diego Trough) and beyond the sand-silt area, the sediment is a pale olive-gray silt with minor amounts (less than 15 per cent) of very fine sand and clay. Isolated patches of this material also occur on the floor of Coronado Canyon near its head and on the outer edge of the shelf in the vicinity of latitude 32°36′. The gray silt is the most extensive of all the unconsolidated sediments, covering about 350 square statute miles (46 per cent) of the total submarine area. Most of the coarser constituents are angular and slightly coated with a green to gray-brown stain.

Minor sediment types.—Among the clastic sediments are several types, of small areal extent, that do not belong to the sediments already discussed. The first of these is a light-olive-gray sand–silt–shell sediment which occurs on the eastern slope of Loma Sea Valley in the vicinity of latitude 32°37′. It differs from the surrounding sand-silt chiefly in its higher percentage of coarse shell fragments.

Just west of Middle Coronado Island is another sediment type similar to the fine gray sand to the north but containing a fairly high percentage of shell fragments.

A third minor type of clastic sediment is a very light-gray mud, composed predominantly of silt and clay (shown as silt in fig. 7). This was found during World War II in an isolated patch associated with boulders off Coronado Strand at latitude 32°38′. It resulted from the pumping of fine muds from the floor of San Diego Bay over Coronado Strand to the open sea in 1942, just prior to the collection of samples. By 1950, wave and current action had removed these fine sediments.

Another local type occurs along the east side of Point Loma and in the entrance of San Diego Bay. This consists of poorly sorted gravel-sand-silt.

CALCAREOUS ORGANIC SEDIMENTS

General.—Although the calcareous organic sediments cover only 8 per cent of the offshore area, they are in several respects the most interesting of all the modern sediments. Perhaps the most striking feature is the general correspondence of their areal distribution to outcrops of bedrock and deposits of boulders and cobbles (figs. 4 and 7). Thus they occur only in areas where clastic sediments are not accumulating now or where their rate of accumulation is exceedingly slow.

The organic sediments are limited to Coronado Bank and to the shelf west and south of Los Coronados Islands. They generally contain appreciable quantities of nonorganic material, which in some places is evidently detrital but which elsewhere appears to be residual from the underlying bedrock upon which the organic sediments rest. Classified on the basis of composition and texture, these sediments are divided into three types.

Foraminiferal fine sand.—The organic sediment of greatest areal extent is a fine pale-olive foraminiferal sand. This material covers most of the top of Coronado Bank and is present in one isolated patch on the ridge north of Coronado Bank and in three small areas near the edge of the shelf south of Coronado Canyon. Samples consist principally of tests of planktonic and benthonic Foraminifera and contain a smaller but appreciable quantity of shell fragments, glauconite, and coprolites. Clay casts in many of the foraminiferal tests are also abundant in the bank sediments. They will be discussed in more detail in a later section of this report.

Detrital grains range from very little to more than half of the material. They vary from coarse sand to silt, grading into the finer sizes near the boundary between the foraminiferal sand and the sand-silt areas. Most of the detrital grains are subangular to subround and are coated with a light greenish-gray stain.

Foraminiferal medium to coarse sand.—A pale-olive foraminiferal medium to coarse sand occurs on the shoaler portions of Coronado Bank. This is similar to the foraminiferal fine sand except for the coarser texture of the detrital grains. In many samples detrital grains of coarse and medium sand make up approximately 50 per cent of the material. Most of them are subround, but some are subangular to angular. Many are coated with a light-gray stain.

Shell sand.—The third type of calcareous organic sediment is a very pale-brown to light-grayish-brown coarse shell sand. This is confined principally to the area surrounding Los Coronados Islands and to a narrow strip of the shelf between the 20- and 30-fathom contours and trending southeasterly from the islands. Throughout most of this area the sediment consists almost entirely of coarse shell fragments, but near the islands the shell sand is mixed with gravel, sand, and silt in varying proportions. These detrital grains are mostly subangular to subround and are coated with a yellowish-brown to gray stain. In contrast, the detrital grains near the boundary of the shell-sand area are similar to those of the adjacent clastic sediments, being mostly angular to subangular and only slightly stained.

MIXED CLASTIC AND CALCAREOUS ORGANIC SEDIMENTS

The sediments that consist of approximately equal proportions of calcareous organic and clastic constituents have the smallest areal extent of the three groups of unconsolidated materials. They are confined mainly to a narrow strip bordering the west side of Point Loma and extending for approximately 4 miles south of the tip of Point Loma (fig. 7). About a mile farther south is a small, isolated area of similar material. Possibly these areas were formerly continuous, and their juncture has been obscured by a cover of fine gray sand. The continuity of the mixed sediments near the west side of Point Loma may not be correct, as shown in figure 7, because of the scarcity of near-shore samples in that area.

The mixed sediments range from very

light gray to medium olive-gray and consist of approximately equal amounts of coarse broken shells and of granules and pebbles. Near its boundary with the area of fine gray sand the mixed sediment contains some fine sand and silt.

TEXTURE

GRAIN SIZE

Enough sediment for satisfactory analysis was present in 1,225 of the 1,300 samples available. So much time would have been required to make conventional mechanical analyses of so many samples that a rapid visual comparison method was developed (Emery and Gould, 1948). To serve as standards, 166 of the samples were analyzed by the usual screening and pipetting method.

The median diameters of all 1,225 samples were found to range from 0.011 to 2.0 mm. All analyses included both clastic and calcareous grains but excluded gravel. If gravel had been included in the analyses, larger medians would have resulted for some samples. Nearly 50 per cent of the samples have medians within one ϕ unit (one Wentworth grade size—see fig. 8) of 0.125 mm., thus being classified as fine sand or very fine sand. An approximation of the over-all size distribution of the sediment was obtained from the weight percentage in each size grade of the 141 conventionally analyzed samples from the shelf shallower than 100 fathoms and of the 25 samples from deeper water. These were totaled and plotted as though for two composite samples. The resulting plot (fig. 9) shows that the median diameter of the composite sediment from the shelf and bank is 0.137 mm., whereas that of the deeper sediment is only 0.038 mm.

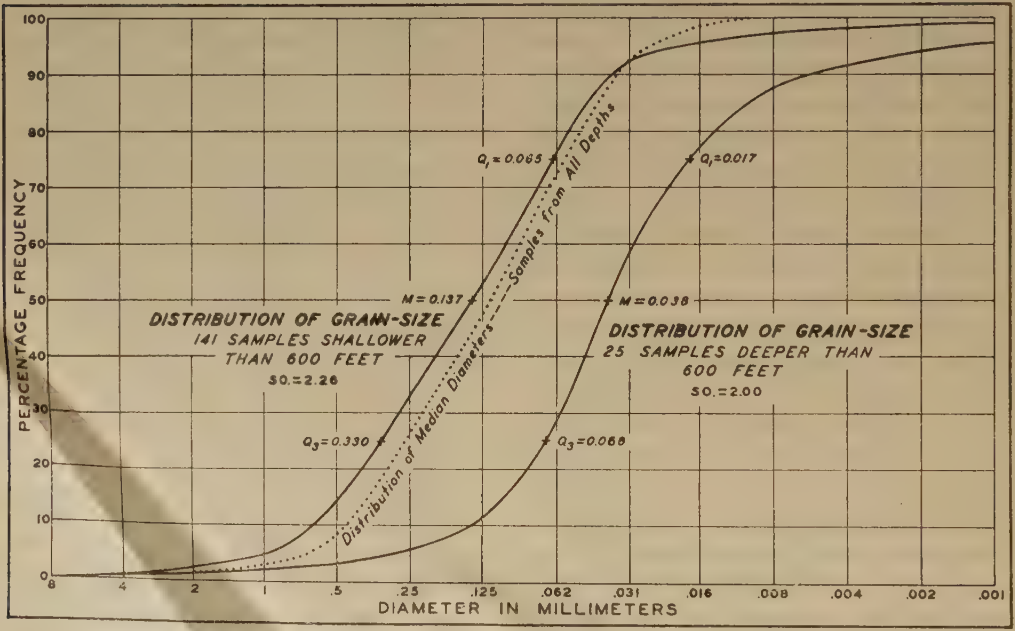


FIG. 9.—Distribution of grain sizes in an average sample from the shelf and bank top (less than 100 fathoms) and from deeper water (more than 100 fathoms). Both were compiled by averaging the weight percentage of each grade size in all samples. For comparison, the distribution of median diameters of samples from all depths is shown by a dotted line.

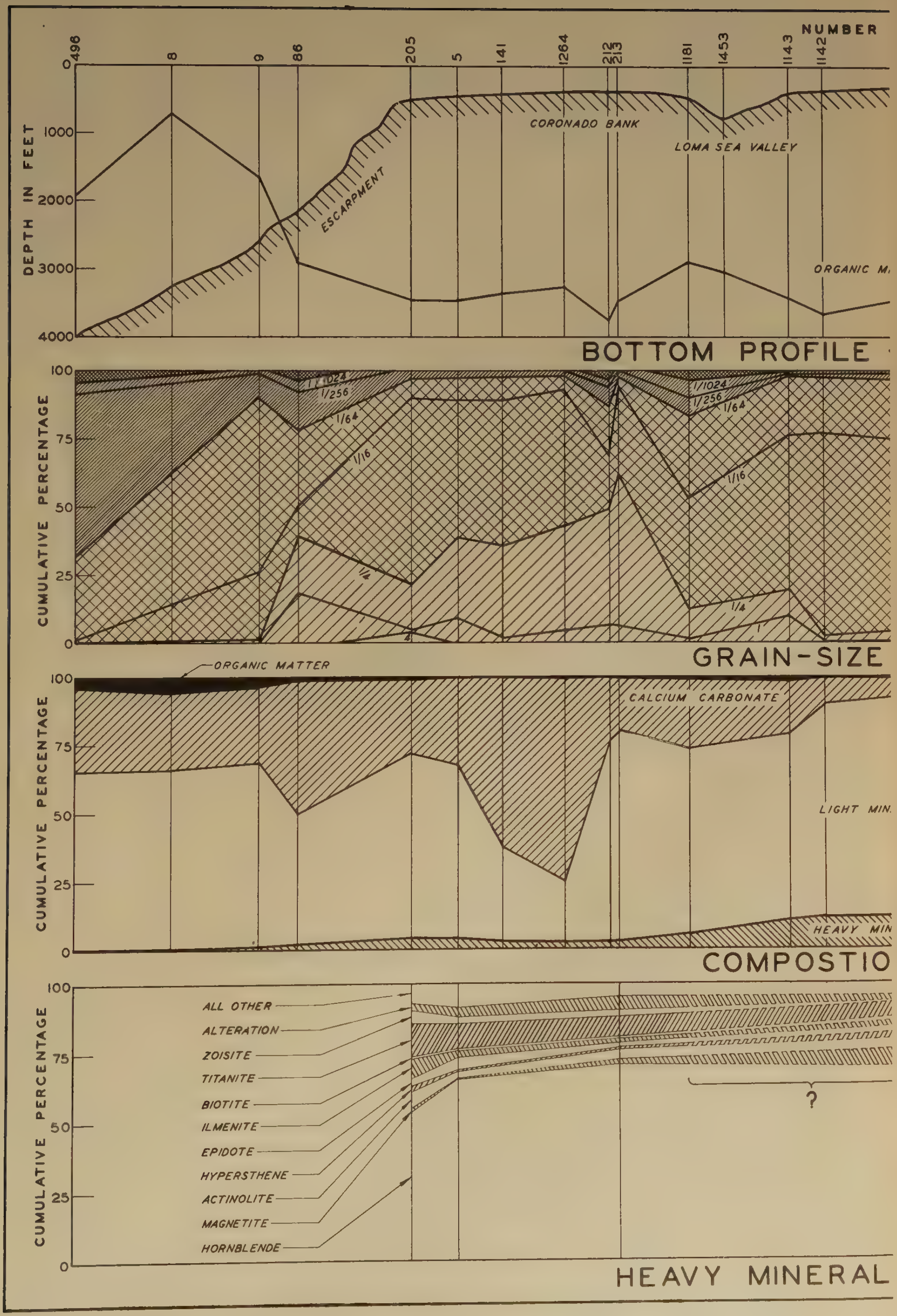
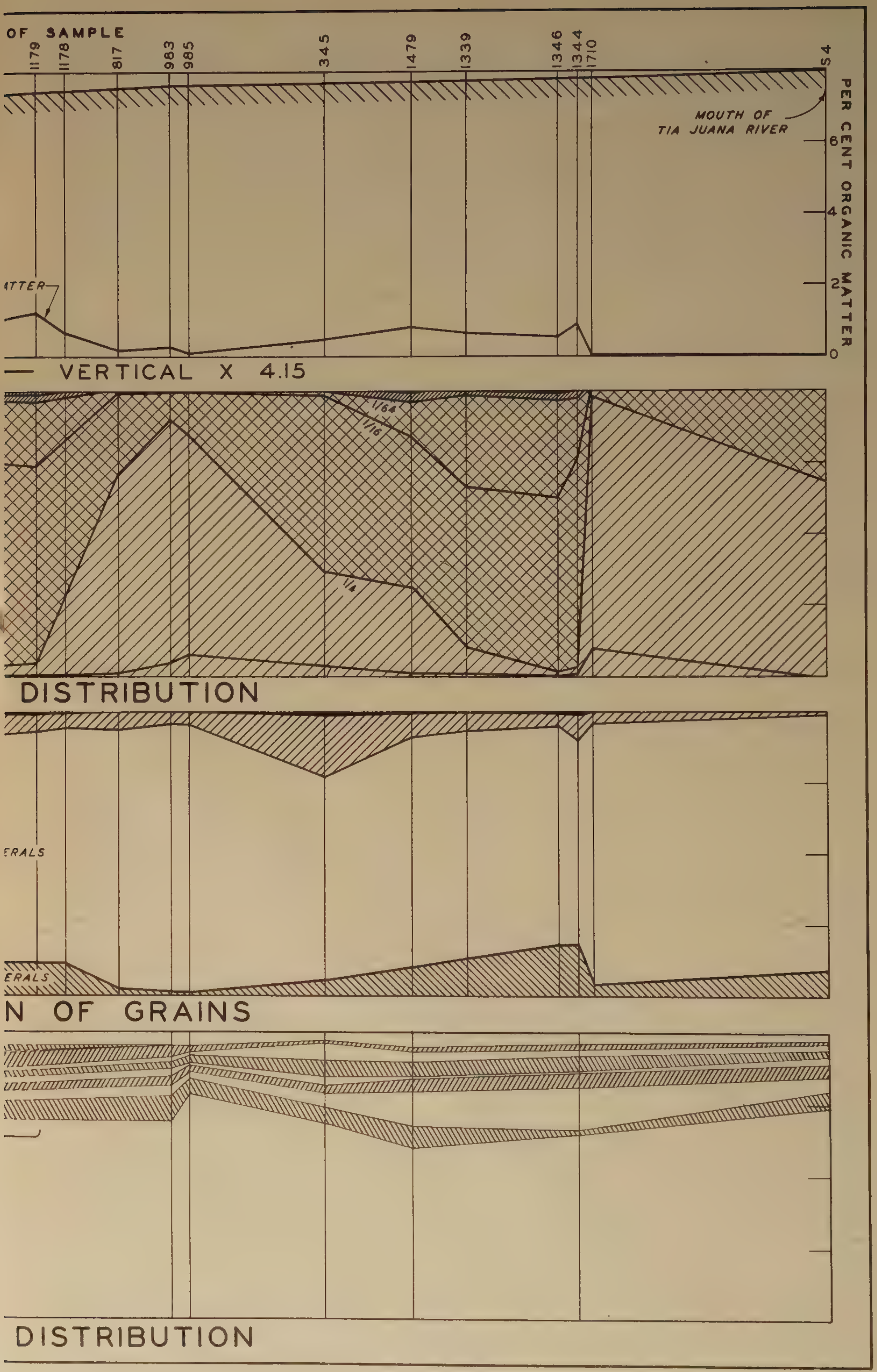


Fig. 10.—Cross section from mouth of Tia Juana River westward across shelf, Loma Sea Valley, Coronado in samples along the section are shown.



Bank, and top of Coronado Escarpment. The grain size, general composition, and chief heavy minerals

The medians of all samples were plotted on a map at the positions of the sampling sites. Isopleth lines at one ϕ unit intervals were drawn and shaded by cross-hatching. The resulting figure 8 shows that the coarsest sand (-2–0ϕ, or 4–1 mm.) is close to the cliffed shores of Los Coronados Islands. Intermediate sand (0–2ϕ, or 1–$\frac{1}{4}$ mm.) forms a broad zone along the coast, except off Coronado Strand, where it is separated from the shore by a large zone of finer sand. It also borders the coarse sand of Los Coronados Islands and occurs atop Coronado Bank. Finer sand (2–4ϕ, or $\frac{1}{4}$–$\frac{1}{16}$ mm.) mainly occupies a wide area off Coronado Strand and occurs also in strips fringing the intermediate sand. The fourth main category of sediment, silt (4–6ϕ, or $\frac{1}{16}$–$\frac{1}{64}$ mm.) occurs chiefly in the deeper water of the bottom and side of San Diego Trough, in Loma Sea Valley, and at the head of Coronado Canyon. The finest sediment of the entire region was discovered outside Coronado Strand in depths of only 6–9 fathoms and fully exposed to the waves. As previously stated, this anomalous occurrence resulted from the pumping of fine muds from the floor of San Diego Bay over the strand to the open sea.

The distribution of grain sizes from the shoreline to the Coronado escarpment is illustrated by a cross section in figure 10. This clearly shows the patchy areas of coarse and fine sand on the shelf, the fine sediment in Loma Sea Valley, the coarsening on Coronado Bank, and the marked decrease in grain size on the escarpment leading down to the San Diego Trough. Exposed bedrock and gravel were omitted, to simplify the drawing.

SORTING

Sorting coefficients for conventionally analyzed samples range from 1.18 to 5.56. As shown by figure 11, this distribution is such that 95 per cent of the samples have sorting coefficients smaller than 2.5 and, according to Trask's limits, would therefore be considered well sorted. Sorting coefficients of the individual samples are widely scattered with respect to grain size, but reference to figure 9 shows that the theoretical composite sample from depths of less than 100 fathoms and the one from deeper water have coefficients of 2.26 and 2.00, respectively. These values are in the reverse order of what might be expected from Inman's (1949) analysis of sorting coefficients in the light of fluid mechanics, wherein he found the best sorting for sediment of 0.18 mm. median diameter and progressively poorer sorting for coarser and finer sediments. However, his study was necessarily based on detrital grains that are in equilibrium with the currents, in contrast to the shelf sediments that are a composite of detrital, residual, organic, and authigenic grains, mostly too coarse to be affected by present-day currents. Had mechanical analyses been made for the insoluble residues, the shelf and bank sediment would have been coarser and better sorted than the sediment from deeper than 100 fathoms. Comparison of the actual relationship of sorting and grain size with the equilibrium relation-

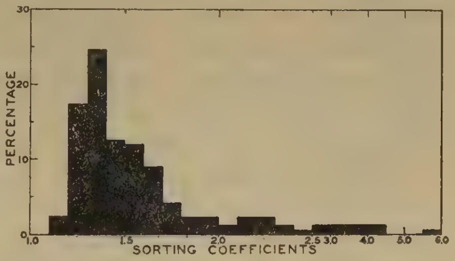


FIG. 11.—Histogram showing variation of sorting coefficients of 158 unconsolidated sediment samples in all depths.

ship thus offers a means of judging whether the detrital fractions were deposited under present or past conditions.

ORGANIC CONSTITUENTS

CALCIUM CARBONATE

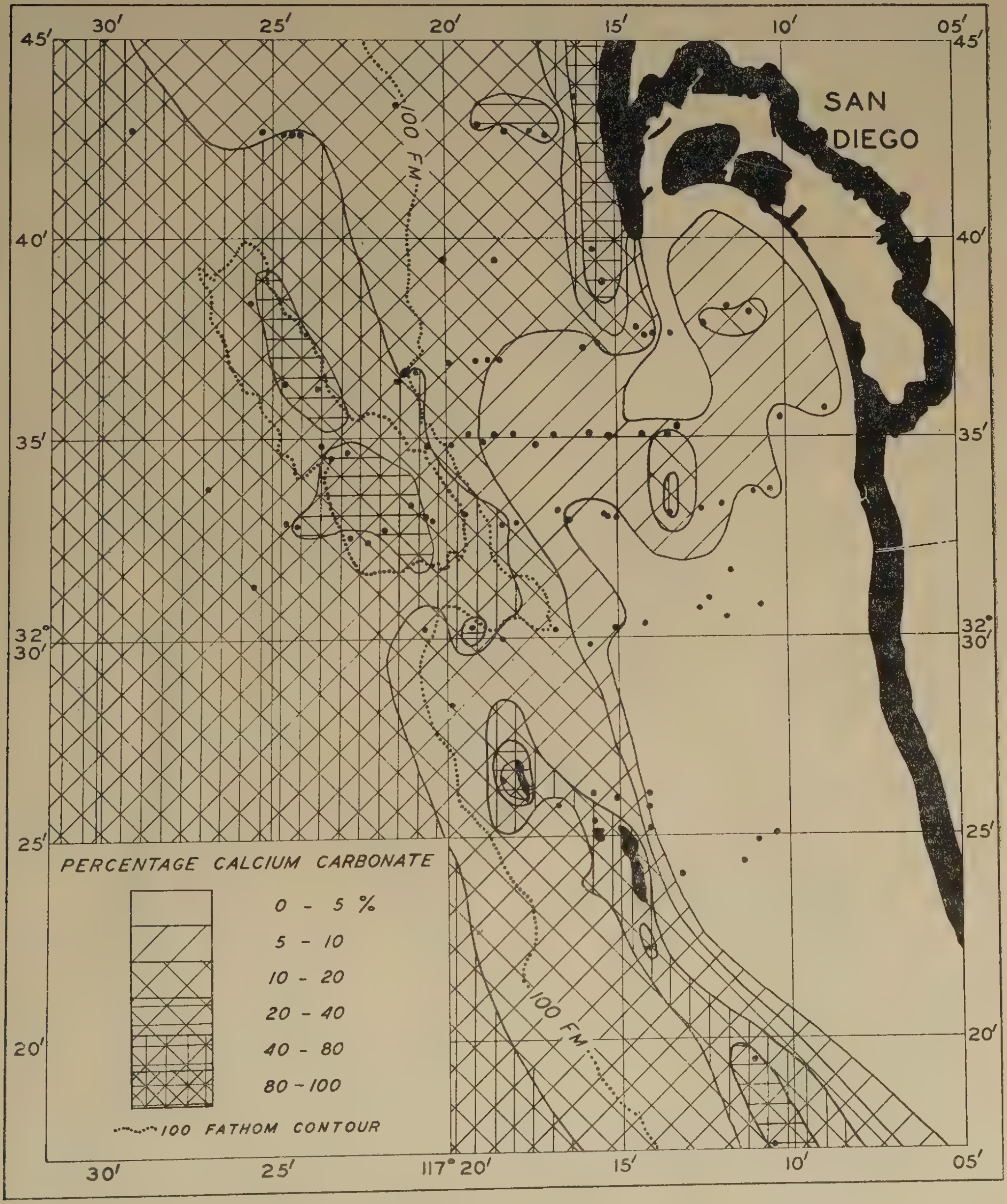
The percentage by dry weight of material soluble in dilute hydrochloric acid was determined for 108 samples. The soluble fraction is termed "calcium carbonate," though it contains, in addition, small quantities of magnesium carbonate, collophane, and other compounds. The bulk of this "calcium carbonate" is in the form of benthonic and pelagic foraminiferal tests and broken fragments of pelecypod shells and bryozoans. The median value for all samples is 11 per cent, whereas that for samples deeper than 100 fathoms is 21 per cent.

Isosol lines (fig. 12) were drawn for the area on the basis of 108 analyses aided by visual comparison of numerous other samples with the analyzed set. The isosol lines were chosen on a logarithmic progression (5, 10, 20, 40, and 80 per cent) because of the wide range of values (0.8–86.7 per cent). Owing to the small number of analyses, the lines are broadly curving. A denser control would have revealed numerous irregularities and obscured the simple general picture. The chart (fig. 12) shows that less than 1 per cent soluble material occurs in the beach sands of Coronado Strand and less than 5 per cent in the sand immediately offshore of Coronado Strand, in the belt south of Point Loma, and in a wide strip off the Mexican portion of the area. Off the Tia Juana River calcium carbonate increases toward the outer part of the shelf until, at Loma Sea Valley, about 15 per cent is present. The sediments on the top of Coronado Bank are characterized by very high percentages of calcium carbonate, usually more than 50 per cent. A high content also exists on the shelf edge south of Coronado Canyon. Beyond the shelf edge and on the slope and floor of the San Diego Trough the calcium carbonate content has a fairly uniform value of about 25 per cent.

Along the shore the shells apparently become so broken up by wave and current action that solution is rapid. Also, near shore the calcium carbonate is much diluted by detrital sediment. Farther offshore, where detrital sediment is deposited less rapidly, as indicated by the finer grain size, calcium carbonate is more abundant. Still farther out, Loma Sea Valley and Coronado Canyon trap or divert detrital sediment coming from the mainland, so that little of it reaches the top of Coronado Bank. As a result, the sediments of the bank contain a high percentage of calcium carbonate. Other rocky areas which lack clastic deposits, such as the area directly west and south of Point Loma and the outer shelf near Los Coronados Islands, are also characterized by high calcium carbonate content. Dilution by fine sediment offshore in the San Diego Trough results in a slightly decreased percentage of calcium carbonate. The fairly uniform conditions of deposition in the trough are reflected by a uniform percentage of calcium carbonate.

ORGANIC MATTER

Organic carbon was determined for 26 samples by the empirical method of oxidation with potassium dichromate and back-titration with ferrous ammonium sulfate, as described by Allison (1935). These values were converted to total organic matter by multiplying by 1.7, a factor used by soil chemists. The highest values of total organic matter were found for four samples from the escarpment. These averaged 4.4 per cent. Six samples from the bank top averaged 1.1 per cent, three from the bottom and sides of Loma Sea Valley averaged 2.0 per cent, twelve from the shelf inshore from Loma Sea Valley averaged 0.5 per cent, and the single sample from the beach contained no organic matter. Thus there is an increase of organic matter from shore toward deep water (fig. 10). This is in agreement with results obtained by Trask (1932) in a more general survey of the sea floor off southern California.


30′
25′
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45′
40′
35′
32°
30′
25′
20′
SAN DIEGO
100 FM
100 FM
PERCENTAGE CALCIUM CARBONATE
0 - 5 %
5 - 10
10 - 20
20 - 40
40 - 80
80 - 100
100 FATHOM CONTOUR
30′
25′
117° 20′
15′
10′
05′

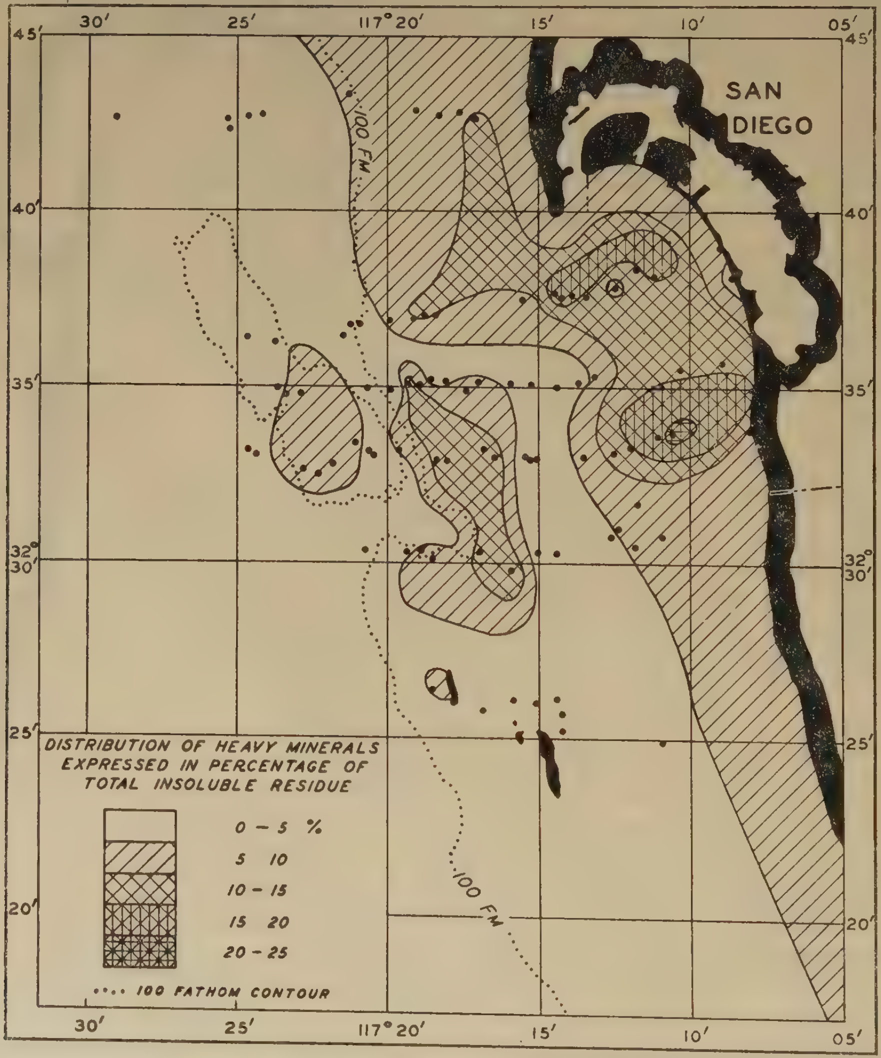
FIG. 12.—Distribution of calcium carbonate in unconsolidated sediments

MINERAL COMPOSITION

DISTRIBUTION OF TOTAL HEAVY MINERALS

Separation of heavy minerals in bromoform was made on the insoluble residues of 95 unsieved sediment samples. The results, computed on a whole-sample basis and plotted in chart form, show a distribution that is complicated by local differences in organic calcium carbonate and in grain size. Computed on a whole-sample basis, the mean value of the heavy-mineral content is 4.4 per cent, whereas on a calcium carbonate-free basis it is 6.2 per cent. The latter is a better figure for use in estimating provenance, because the calcium carbonate is not detrital but a diluent of organic origin.

The heavy minerals expressed in percentage of the insoluble residues (fig. 13) are most abundant in two zones. One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SAN
DIEGO
100 FM
100 FM
DISTRIBUTION OF HEAVY MINERALS EXPRESSED IN PERCENTAGE OF TOTAL INSOLUBLE RESIDUE
0 – 5 %
5 10
10 – 15
15 20
20 – 25
100 FATHOM CONTOUR

FIG. 13.—Distribution of heavy minerals in unconsolidated sediments expressed in percentage of insoluble residue.

zone (of 15–25 per cent) is near shore in the broad open bay off Coronado Strand and the Tia Juana River, and the other (of 10–15 per cent) is in deeper water skirting the head of Coronado Canyon. The highest individual percentage occurs immediately off the Tia Juana River, which is believed, therefore, to be the most important source of the heavy minerals. In the first zone the whole samples consist of fine sand, whereas in the second the samples are of very find sand to coarse silt. The coarse sand of the intervening area has less than 5 per cent of heavy minerals. Similarly, offshore on the escarpment and in the bottom of San Diego Trough the silt and clay have less than 5 per cent of heavy minerals.

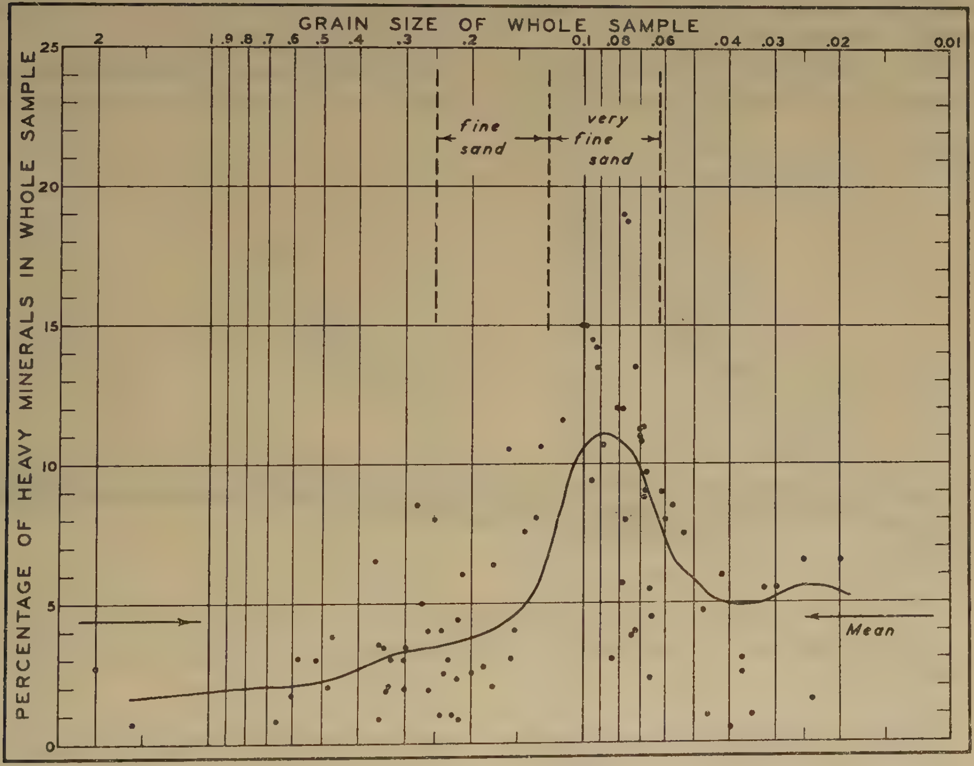

FIG. 14.—Dependence of percentage of heavy minerals of whole sample upon median diameter of whole sediment.

A comparison of figures 8 and 13 shows that the grain size exerts very great control over the content of heavy minerals. The highest percentages of heavy minerals occur in fine to very fine sand, whereas low percentages occur in both coarse sand and fine silt and clay. This relation must mean that the heavy minerals have a narrower size range than the light minerals and that most of the heavies are restricted to the finest sand sizes. Sieving of the heavy-mineral separates showed that a median of 70 per cent by weight of the heavy minerals lay between $\frac{1}{16}$ and $\frac{1}{4}$ mm. in diameter. Figure 14 further illustrates the dependence of heavy-mineral content on grain size. It is apparent that the heavy minerals are more than twice as abundant in samples having a median diameter between $\frac{1}{16}$

and $\frac{1}{4}$ mm. than in either coarser or finer sediments. In addition, the median percentage of heavy minerals in the separated $\frac{1}{16}$–$\frac{1}{4}$-mm.-size fraction of each sample was found to be 9.2, more than twice the over-all percentage in the whole sample. An even greater dependence on grain size would have been indicated, had the median diameters of the insoluble residues been available.

This relationship of percentage and composition of heavy minerals to grain size has been known for a long time, but usually it is ignored in heavy-mineral investigations. Its great importance is also shown in Van Andel's (1950) investigation of Rhine River sediments.

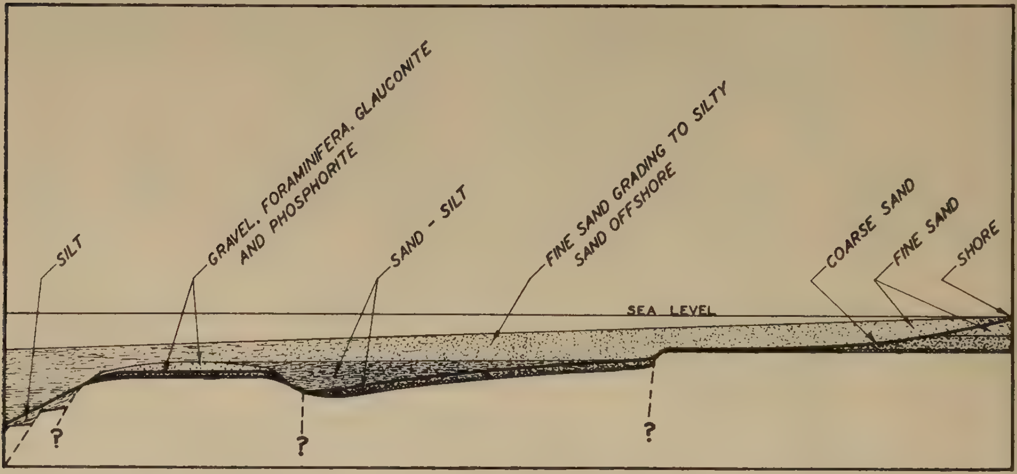
SILT
GRAVEL. FORAMINIFERA. GLAUCONITE AND PHOSPHORITE
SAND - SILT
FINE SAND GRADING TO SILTY SAND OFFSHORE
COARSE SAND
FINE SAND
SHORE
SEA LEVEL
?
?
?

FIG. 15.—Diagrammatic cross section of present and future sea floor off San Diego. Heavy line indicates present sea floor.

MINERAL PROVINCES

General.—The minerals of 34 samples were identified in an attempt to differentiate further between the various sediment types and to investigate their possible sources. Owing to the difficulty of identifying minerals of silt and clay size, only samples from the areas of coarser sediment were studied. These samples were selected so as to conform as closely as possible to the major sediment province already discussed. The samples are grouped as follows: 4 from Coronado Strand, 9 from the medium to coarse gray- and brown-sand areas, 11 from the fine-gray-sand areas, 7 from the foraminiferal sand of Coronado Bank, and 3 from the shell sand surrounding Los Coronados Islands.

The percentages of quartz, orthoclase, plagioclase, and other constituents of the light fraction were identified chiefly by selective stains (Gabriel and Cox, 1929) and the heavy minerals by the usual optical methods. Percentages are based on counts of approximately 400 grains in each sample. Throughout the study, the whole heavy-mineral separation was used rather than a sieve fraction.

Because of their petrographic similarity, the individual analyses of samples from each province have been averaged, and the results are presented in table 4 under the headings of "Organic," "Authigenic," "Light Detrital," and "Heavy Detrital" minerals. One of the most in-

TABLE 4

Mineral Composition of Modern Sediments

Mineral Species	Coronado Strand (Av. of 4 Samples) (Per Cent)		Medium to Coarse Gray and Brown Sand (Av. of 9 Samples) (Per Cent)		Fine Gray Sand (Av. of 11 Samples) (Per Cent)		Foraminiferal Sand, Coronado Bank (Av. of 7 Samples) (Per Cent)		Shell Sand Los Coronados Islands (Av. of 3 Samples) (Per Cent)	
Organic:										
Calcite	.....	2.4	.....	3.9	.....	9.0	.....	37.2	.....	36.4
Authigenic:										
Glauconite	0.0		0.0		0.0		24.0		0.0	
Clay casts	0.0		0.0		0.0		75.9		0.0	
Collophane	p*		p		p		0.1		p	
	p	p	p	p	p	p	100.0	17.4	p	p
Detrital lights:										
Quartz	49.7		56.8		70.8		69.0		48.5	
Plagioclase	38.4		35.8		25.8		26.2		30.9	
Orthoclase	11.5		7.0		2.6		4.8		18.1	
Muscovite	0.0		0.3		0.8		0.0		0.0	
Rock fragments	0.4		0.1		0.0		0.0		2.5	
	100.0	88.4	100.0	91.6	100.0	80.9	100.0	42.6	100.0	60.2
Detrital heavies:										
Hornblende	72.1		70.4		59.4		58.0		21.1	
Actinolite	5.2		4.1		8.1		4.7		2.6	
Magnetite	4.9		3.5		3.8		0.9		0.0	
Ilmenite	3.8		4.9		3.7		4.6		3.7	
Barite	2.6		3.0		1.6		0.8		0.6	
Hypersthene	2.6		3.9		2.8		0.5		0.0	
Biotite	1.8		1.8		14.2		0.6		0.0	
Epidote	1.6		1.4		1.7		4.1		10.1	
Zoisite	1.1		0.2		0.7		2.6		3.1	
Garnet	0.8		1.0		0.2		1.3		1.8	
Sphene	0.8		2.7		1.5		8.8		10.1	
Apatite	0.5		0.2		0.3		0.9		0.0	
Leucoxene	0.5		0.7		0.3		1.4		4.3	
Chlorite	0.5		0.3		0.5		1.1		1.9	
Basalt. hb.	0.4		0.4		p		0.5		0.0	
Zircon	0.4		0.2		0 4		0.4		0.0	
Glaucophane	0.2		0.0		0.3		0.5		0.0	
Olivine	0.2		0.7		0.1		1.9		0.0	
Enstatite	0.0		0.4		p		0.0		0.0	
Hematite	0.0		0.2		0.1		0.0		2.0	
Limonite	0.0		p		0.0		0.0		0.6	
Anatase	0.0		0.0		0.3		0.0		0.0	
Alteration	0.0		0.0		0.0		5.7		36.3	
Augite	0.0		0.0		0.0		0.5		1.8	
Diopside	0.0		0.0		0.0		0.3		0.0	
	100.0	9.2	100.0	4.5	100.0	10.1	100.0	2.8	100.0	3.4
		100.0		100.0		100.0		100.0		100.0

* "p" indicates present in amounts less than 0.1 per cent.

teresting general features shown by these data is the high percentage of feldspar and the marked abundance of plagioclase relative to orthoclase. Plagioclase is about three times as abundant as orthoclase, and the total feldspar content of all samples averages about 30 per cent; thus the sediment is properly termed an "arkose." The great proportion of feldspar in itself is not unusual, since most of the Cretaceous and Cenozoic sandstones in California are feldspathic (Reed, 1933, pp. 276–277), owing to the still higher feldspar content of the batholithic source rocks. However, it is of interest that sediments very similar to those of past geologic periods in California are present on the sea floor today.

Inshore areas.—The mineral assemblages of the inshore areas (Coronado Strand, the medium to coarse gray and brown sand, and the find gray sand) are very similar (table 4) and therefore can be discussed together. Unlike the Coronado Bank and Los Coronados Islands areas, the sediments of the inshore areas are almost entirely detrital. The most striking feature of their heavy constituents is the abundance of green hornblende. This, together with the high percentages of actinolite, magnetite, barite, and hypersthene and the low percentages of epidote, zoisite, and sphene, suggests that the sands of the inshore areas have a common source; but this does not necessarily mean that they are of the same age.

The only notable exception to the general similarity of minerals in all the inshore areas is the unusual abundance (14.2 per cent) of brown biotite in the fine gray sand southeast of Point Loma. Because of its platy habit, biotite is easily removed from the beach by wave and current action and carried to deeper water. The fact that biotite is more easily transported than most other minerals is apparent from the large size of the biotite flakes in the fine gray sand. Most of these flakes are several times larger than the median diameters of the whole samples. The same explanation applies to the absence of appreciable amounts of biotite in the coarser-sand zones off the mouth of the Tia Juana River, where the presence of medium to coarse sand may indicate that the currents in that region are capable of keeping biotite in suspension with the finer materials until they reach deeper water.

Coronado Bank.—In contrast to the predominantly detrital sediments of the inshore areas, the sediments flanking Los Coronados Islands and those lying on top of Coronado Bank are distinguished by their high percentages of organic constituents. As previously mentioned, the sediments in the vicinity of the islands consist largely of coarse shell fragments, and those on the bank are chiefly foraminiferal tests. Although the organic calcium carbonate content of many samples from these areas exceeds 50 per cent, the average percentage of calcareous material in the samples selected for mineral analysis is 37.2 per cent for the Coronado Bank samples and 36.4 per cent for the Los Coronados Island area samples.

In addition to its high percentage of calcareous organic sediment, Coronado Bank is further distinguished by an appreciable quantity of authigenic minerals. Chief of the latter are internal casts of clay and glauconite in many of the foraminiferal tests. These casts range from light buff through tints of green to dark green and black. This color transition suggests that there may be a genetic connection between the clay casts and the formation of glauconite, but proof of this relation must await chemical and X-ray studies. Some of the glauconite occurs in the form of coprolites, but, because of their scarcity, they have not warranted a separate entry in table 4. Another minor authigenic constituent is collophane, which probably has the same origin as the larger phosphorite nodules of the bank. It seems probable that the formation of this mineral is confined to the bank and that the few grains of collophane in samples from the other areas are detrital.

The detrital constituents of the Coronado Bank sediments are considerably more rounded and more highly weathered than those of the inshore provinces. It is inconceivable that the coarse bank sediments could be transported across Loma Sea Valley and deposited on top of Coronado Bank under present conditions. The same general suite of heavy minerals characteristic of the inshore areas is also present in the bank sediments, but there are some notable differences in their percentages. Highly altered grains, expressed as "alteration" in table 4, are fairly common (5.7 per cent of the heavies) in the bank samples, but no grains of this type were found in samples from the inshore areas. Similarly, sphene, epidote, and zoisite are considerably more abundant on Coronado Bank, and magnetite and hypersthene, which are common in the inshore areas, are rare on Coronado Bank. These factors suggest that the bank sediments have a different source and are of greater age than some of the inshore sediments.

Los Coronados Islands area.—The detrital minerals of the shell sand surrounding Los Coronados Islands, like those of Coronado Bank, exhibit a greater degree of rounding and are more highly weathered than the minerals of the inshore provinces. The general coarsening of these sediments toward the islands suggests that they are locally derived. The most striking difference between the heavy minerals of this province and those of the other mineral areas is the comparatively low percentage of green hornblende and the great abundance of altered minerals (compare tables 1 and 4). Titanite, epidote, and zoisite are much more prominent in the island area, whereas magnetite and hypersthene, which are common in the inshore areas, are rare or absent. The occurrence of a considerable amount (4.3 per cent) of leucoxene and the marked decrease in actinolite further differentiate the Los Coronados Islands area sediments from those inshore.

CONCLUSIONS

TOPOGRAPHY AND STRUCTURE

Knowledge of the structure of an area depends on detailed geological mapping, which is impracticable beneath the sea at the present time. Accordingly, only the larger structural framework can be discerned, chiefly from the topography. On the adjacent land the sedimentary rocks overlap the basement complex to the east and dip prevailingly to the west at low angles. Folding is minor, but faults complicate the structure, at least north of San Diego.

The dominant topographic features of the submarine area are: (1) the narrow shelf; (2) the elongate ridge rising as an island group on the outer edge of the shelf and progressively deepening to the north as a shallow ridge, a flat-topped bank, and a narrow deep ridge; (3) the longitudinal valley and the transverse submarine canyon which separate the bank and deep ridge from the shelf; (4) the steep straight escarpment bordering the shelf and the bank; and (5) the broad flat trough at the base of the escarpment. The latter resembles escarpments on the flanks of mountain ranges in southern California that have usually been interpreted as fault scarps, and it is also similar to others of the sea floor that give the region the appearance of a submerged basin and range province wherein faulting predominates over folding.

Coronado Bank is bounded on the seaward side by Coronado Escarpment and on the landward side by Loma Sea Valley. This valley is relatively straight, it parallels the escarpment, and it is asymmetrical in cross section. Extensive faulting is present on Los Coronados Islands nearly on its strike. These features suggest that the valley was cut along a fault or was formed by faulting, either case leading to a separation of the bank from the shelf. The fact that the top of the bank is locally somewhat shallower than the edge of the shelf suggests that it may have been upthrust between two bounding faults. It may be part of a sliver block at the edge of the shelf, whose uptilted end is marked by Los Coronados Islands and whose downtilted end is the deep ridge north of the bank. The age of deformation in the submarine section cannot be determined with any great degree of accuracy, though some of it must have been post-Pliocene, because late Pliocene to late Pleistocene strata have been affected. Most of it must have been pre-late Pleistocene, however, because of the general similarity of depths along the shelf and on the bank, that surface being at least as old as late Pleistocene.

Coronado Canyon, that completes the isolation of Coronado Bank, is transverse to the structural trend, is winding in plan, and has a relatively even outward slope. If the canyon and valley system is erosional, it is likely that Loma Sea Valley was formed first along a fault zone and that Coronado Canyon cut across the ridge at a low point and captured the stream flowing down the valley. Conceivably, such piracy may have resulted from turbidity currents, but the topography is more suggestive of stream erosion, because the ridge would have been a poor source of sediment for turbidity currents. A delta outside the water gap is suggested by the deep and flat top of the great fan which extends out into San Diego Trough at the mouth of Coronado Canyon. If the area were once about 500 fathoms higher than now, stream erosion could have produced the valley system and submarine landslides, and/or turbidity currents could have modified the delta and kept the canyon open after submergence.

AGE OF BEDROCK

Bedrock was obtained from three main areas of the sea floor off San Diego: Coronado Bank, the shelf near Los Coronados Islands, and an area just south of Point Loma. The rocks of the top of Coronado Bank contain Foraminifera and mollusks of late Pliocene to Recent age and have the same suite of heavy minerals as do the Pliocene formations ashore. The beds are truncated by an erosional surface that probably was cut during the last glacial stage of lowered sea-level, thus the rocks are probably older than late Pleistocene. Rocks from the shelf near Los Coronados Islands are unfossiliferous but are lithologically similar to the Miocene rocks of the islands. In the area south of Point Loma the rocks, predominantly shales, contain Cretaceous Chico Foraminifera and are lithologically similar to Cretaceous rocks that crop out on land at the tip of Point Loma.

AGE AND SOURCE OF GRAVELS

Gravels that range from pebbles to boulders are present in all areas of bedrock. The fragments are of two types: sandstone and shale, like the underlying bedrock, and igneous and metamorphic rocks that are partly from underlying conglomerates and partly derived from land and mixed with those of local origin. The gravels are believed to have been deposited during the last stage of glacial lowering of sea-level, because (1) they lie atop a bedrock surface cut probably during the last glacial epoch, (2) some pieces are much too large to be transported or eroded from bedrock by the weak bottom currents of today, (3) associated with them are a few shells that are characteristic of colder water than now covers the area, and (4) they contain abundant pholad borings that are probably characteristic of shallower depths than exist today.

In addition to gravels on bedrock, there are several areas of gravel where no bedrock is known. Largest of these is the boulder patch off the mouth of the Tia Juana River and an area of scattered cobbles off Coronado Strand. These areas are believed to be part of the general distribution during the late Pleistocene. A blanket of gravel may have been deposited throughout the area at that time, but it has been buried beneath finer sediments except in these few areas.

SOURCES OF SEDIMENT

Although the finer unconsolidated sediments have been described in some detail, the investigation is not complete without some inquiry into the sources of the detrital part of the sediments. To aid in this study, all available data on the mineral constituents of the rocks from which the sediments may have been derived are summarized in table 1 for comparison with table 4.

There is a general similarity in mineral composition of all the formations from Cretaceous to Recent, including the unconsolidated sediments of the offshore area. Differences in the percentages of these mineral constituents serve to differentiate the formations, but the general similarity of mineral species strongly suggests that all were ultimately derived from a common source. High percentages of feldspar, hornblende, biotite, and other igneous accessory minerals indicate that the formations have been derived chiefly from intermediate igneous rocks, probably the tonolite batholith that forms the core of the Peninsular Range on the east. Supporting evidence for a relatively local origin is also found in the coarseness, the angularity, and the general freshness of the grains that make up the Cretaceous and Cenozoic sedimentary rocks.

A comparison of the mineral data listed in tables 1 and 4 shows a close resemblance between the medium to coarse gray and brown sand, the fine gray sand, and the beach sands of Coronado Strand and of the whole coast from Point Descanso to Oceanside. As some of the inner-shelf sediments are probably derived from the beaches, it is not surprising that they should correspond so closely.

There is also a close correspondence between the unconsolidated sediments of the inner-shelf areas and the marine Pliocene formations on the mainland. The general similarity in abundance of green hornblende and in percentage of actinolite, biotite, epidote, and ilmenite is striking. It seems quite probable that a considerable proportion of the inner-shelf sediments have been derived from the mainland Pliocene formations because of their wide distribution and their susceptibility to erosion. However, it is equally apparent that some of the inner-shelf sediments must have been contributed by another source, possibly the igneous and metamorphic rocks exposed in the Tia Juana River drainage basin.

In many respects the detrital constituents of the Coronado Bank province appear to be even more closely related to the Pliocene formations on land than are the inner-shelf sands. Such diagnostic minerals as actinolite, sphene, ilmenite, epidote, and zoisite of the Pliocene formations are present in about the same proportions. There are, however, some significant differences in a few constituents. Hornblende, although it is the most prominent heavy mineral in the Pliocene formations, is more abundant in the bank sediments, and biotite, which is fairly common in the Pliocene, makes up only a very small percentage of the bank sediments. Possibly the biotite has been winnowed out of the bank material by current action, causing an increase in the percentage of hornblende. Evidently the detrital sediments on top of Coronado Bank are either reworked Pliocene or were derived from the same general source as the Pliocene formations. Reworking from the underlying Pliocene rocks is considered more probable because of the difficulty of transportation to the bank after its separation from the shelf.

The sediments surrounding Los Coronados Islands have high percentages of epidote, sphene, and altered minerals. These minerals suggest derivation either from Eocene formations on land or from the Miocene rocks of the islands and vicinity. Owing to their coarseness, their high content of rock fragments, and their proximity to the islands, it is more probable that they came from the islands. The presence of hornblende, although much less abundant than in the other mineral areas, probably indicates some admixture of the sediments from the shelf.

CONDITIONS OF DEPOSITION OF THE INNER-SHELF SEDIMENTS

Several lines of evidence suggest that at least two periods of deposition are represented in the finer materials that cover the inner shelf. The first and oldest of these periods is represented by the medium to coarse brown sand and possibly the medium to coarse gray sand, because (1) it is highly improbable that present-day waves and currents in the area can transport coarse sands so far from shore (more than 7 miles) and especially to depths exceeding 20 fathoms; (2) the brown sand is deeply stained with ferric iron oxide and is more highly weathered than other sediments of the inner shelf; (3) fine gray sand, which is now supplied by the Tia Juana River, lies shoreward of the brown-sand area and probably overlaps it.

The general north-south trend of the brown-sand area and its extension in isolated patches to the tip of Point Loma suggest that it was deposited when the shoreline was considerably west of the present position at a time of relatively lower sea-level. The close association of the brown sand with rounded cobbles and boulders very similar to the conglomerates and deeply iron-stained sands covering many of the terraces of the mainland suggests further that the coarse sands on the inner shelf are reworked terrace deposits. According to Ellis and Lee (1921) and Hanna (1926), the prominent stream valleys bordering the ocean were formerly cut to depths of 100–200 feet below their present levels. Alluvial fill in the valleys consists of variable sand and silt atop a layer of well-rounded boulders and cobbles that varies in thickness from 10 to 35 feet. The marked similarity between the boulders, cobbles, and coarse sand at the bottom of the Tia Juana River Valley and the sediments of the coarse sand and the boulder zones in the inshore area is striking.

One hypothesis worthy of consideration is that, when the sea was lowered to the level of the outer shelf and Coronado Bank during a late Pleistocene glacial epoch, extensive nonmarine terrace deposits accumulated on the exposed parts of the shelf. Later, as the sea-level rose, the shore transgressed these deposits, reworking them and leaving an accumulation of coarse, brown, iron-stained sands and gravels. Probably these coarse sediments were widely distributed over most of the inner-shelf region, but only the remnants that have not been covered by present sediments are still exposed.

The second period of sedimentation in the inner-shelf area is presented by the fine gray sand which is contributed by the Tia Juana River at the present time. Part of this detritus has been swept northward by longshore currents to form Coronado Strand, but much of it, particularly the fine sand, is being deposited on the inner part of the shelf. The very fine sand, silt, and clay can be more easily transported than the coarser sediments, so that they reach and are deposited on much of the outer part of the shelf and in the deeper parts of the offshore area.

GEOLOGICAL SIGNIFICANCE

The unusual density of sampling and the relative completeness of background information in this region make it probably the best-known submarine area of its size in the world. As such, it provides information that can be used to help interpret certain sedimentary environments that may be encountered in ancient rocks exposed in outcrops or penetrated by the drill.

The outstanding characteristic is the presence of an unconformity that is only partly buried beneath a blanket of sediment. Where still exposed, the bedrock is associated with a gravel that forms the first deposit above the unconformity. In the depressions of the irregular bedrock surface and especially near the shore, the bedrock and its cover of gravel have been buried by finer sediments. The first layer was of coarse sand; the second (now being deposited) is of fine sand. The second layer and possibly also the first layer are generally thickest in the east near their source. In areas of shallow quiet water, as in San Diego Bay, or in deep quiet water, as in Loma Sea Valley, Coronado Escarpment, and San Diego Trough, silty sediments carried in suspension were and are being deposited atop bedrock, gravel, and sand. In some localities where currents are strong, the shelf is covered by shell fragments, and the bank by Foraminifera, glauconite, and phosphorite. Only if further prograding of the fine sand and thickening of the silt forms a level depositional surface will sediments form layers that are uniform or broadly gradational. This state probably will not be reached until the whole San Diego Trough is filled.

Only the silt of the deeper water contains even moderately high organic matter that may later be converted to oil. The less rich sands interbedded with the silt may eventually serve as reservoir sandstones retaining some of the oil from the silts.

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The Copepod Cyclops dimorphus Kiefer from the Salton Sea

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The Copepod Cyclops dimorphus Kiefer from the Salton Sea

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Plankton samples collected in the Salton Sea, California at irregular intervals since 1944 have consistently yielded a cyclopoid copepod belonging to the tribal section Bifida and the subgenus *Microcyclops* Claus as outlined by Gurney (1933:35).

The number of American species of this subgenus is apparently small. Marsh (1910) found only *Cyclops bicolor*. Wilson (1932) records *C. bicolor* and *C. varicans* under the genus *Microcyclops*. Kiefer (1931) lists the above two species and also *C. rubellus* which according to Sars (1918), Gurney (1933) and Yeatman (1944) is probably a variety of *C. varicans.* In 1934 Kiefer described a new species, *Cyclops dimorphus,* from material sent to him from the Salton Sea. He places the species in his subgenus *Metacyclops* which some authors (Gurney 1933; Yeatman 1944) do not consider distinct from the subgenus *Microcyclops* Claus.

Kiefer's description of *Cyclops dimorphus* is inadequate as already pointed out by Yeatman (1944, p. 72). There appears, however, to be no doubt that the species here dealt with is the one described by him since it is the only cyclopoid noted in the type area and there is agreement with the brief general diagnosis and with the figures of the fifth legs the only parts illustrated in the original description.

It is well, therefore, to give a complete description of the adult of this species, together with an account of the larval development. This is particularly desirable because of the probable bearing the present unusual environment may have on the structure of the species or may later induce should it continue to thrive in the Salton Sea, its new habitat.

Coker (1934) has demonstrated that temperature differences may result in structural variations in certain species of *Cyclops*. Variations occurred in the relative proportions of the caudal rami, and a spine in lieu of a seta was formed on the outer border of the terminal segment of the fourth feet in more than half of the copepods reared at the lower temperatures. The effect of salinity variations or ionic ratios were not studied by Coker.

The Salton Sea is a large body of water lying 248 feet below sea level where it was formed during 1905 to 1907 by overflow of the Colorado River. Subsequent increase in salinity to near that of coastal sea water has resulted from leaching of salt from the old salt bed. Since the formation of this inland sea a number of exotic marine animals have been introduced notably a barnacle, a polychaete worm *Neanthes* and a tintinnid *Favella*. The barnacle appears to have undergone considerable change in shell structure when compared with the type first observed in the Salton Sea about 1942, and has recently been described as a new subspecies *Balanus amphitrite saltonensis* (Rogers, 1949).

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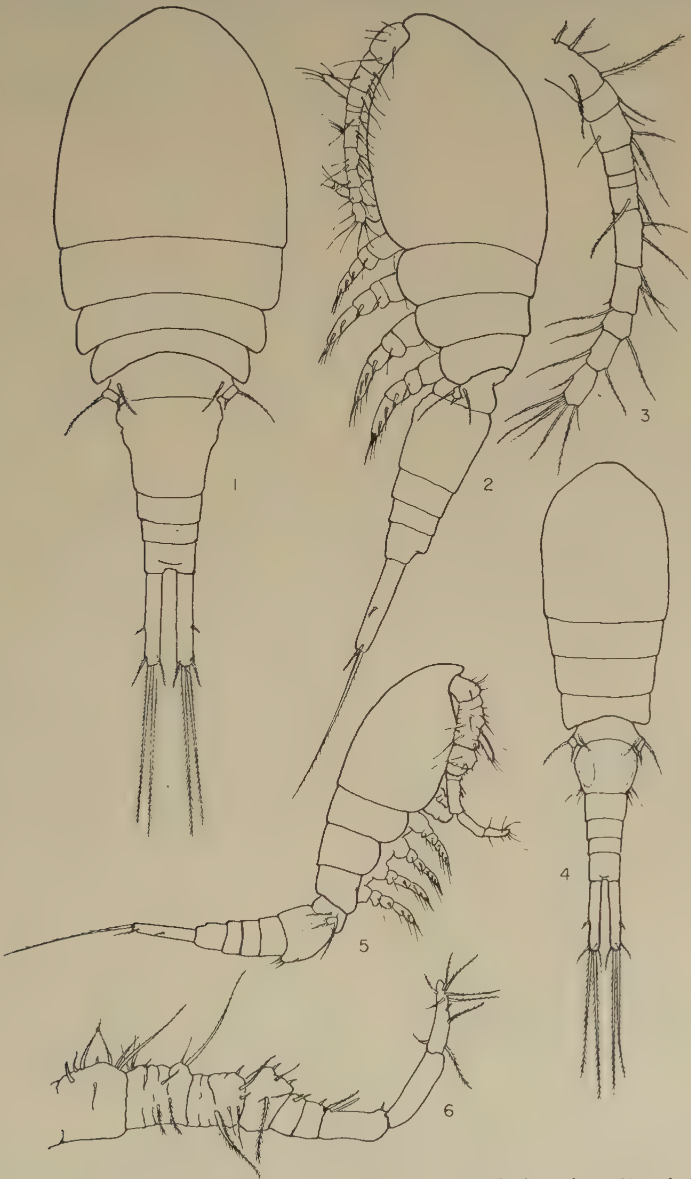
[1] Contributions from Scripps Institution of Oceanography, New Series, No. 589.

The original habitat of *Cyclops dimorphus* has not been determined but it



Figs. 1-6. *Cyclops dimorphus*—1. Female-dorsal; 2. Female lateral; 3. Female-first antenna; 4. Male-dorsal; 5. Male-lateral; 6. Male-first antenna.

seems probable that it will be found in fresh or brackish water of the lower Colorado River.

Plankton tows were taken in Mead Lake (formed by damming of the Colorado River) in 1936 and 1937 and in the Colorado River at Yuma, Arizona and in the Alamo River near El Centro, California on Dec. 22, 1950. The Alamo River receives water from the Colorado River below Yuma and empties into the Salton Sea. *Cyclops dimorphus* was not found in any of these tows though all of them yielded other species of *Cyclops*.

CYCLOPS (MICROCYCLOPS) DIMORPHUS Kiefer, 1934

Figs. 1-18 (camera lucida drawings)

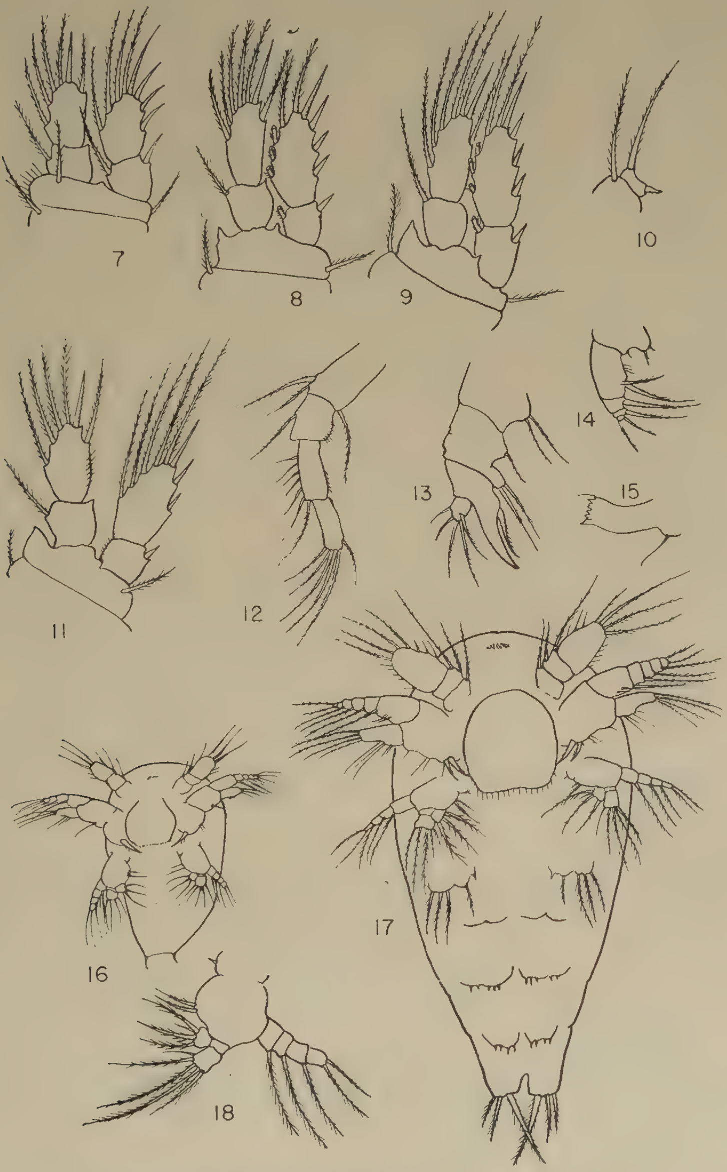
Female.—Body oval, broadest near middle of forebody. Its greatest depth about ¾ the width (Figs. 1, 2). Urosome (without caudal rami) about ½ the length of forebody; genital segment broadest at the anterior end. The caudal rami are about 4 to 5 times as long as broad and are longer than the combined abdominal segments back of the genital segment and about as long as the latter. The terminal caudal setae are about twice the length of the caudal rami and the inner of these setae is slightly the longer. The internal and external caudal setae are nearly equal in length. The outer one is inserted somewhat laterally. The lateral seta is inserted just posterior to the middle of the ramus. The first antennae are composed of eleven distinct segments and are only slightly shorter than the head segment (Fig. 3). The mouth appendages are shown in figures 13-15. The rami of the natatory legs are composed of two segments, the second basis of the first leg bears a long inner spine (Fig. 7). The distal endopod segment of the fourth leg has but one terminal spine (Fig. 11), and there are four inner setae on the segment as opposed to three shown by authors for closely related species. There is no inner seta on the first exopod segment of the fourth leg and the terminal segment has but two outer spines. The fifth legs consist each of one free segment and a broad basal segment confluent with the urosome segment (Fig. 10). The fused segment bears one long seta. The free segment is broad, appearing as a thick lamella and bears a long seta and a strong inner spine. This contrasts with the cone-shaped, slender, free segment found in this position in *C. bicolor* and *C. varicans*, and others.

Length including caudal rami: 0.85-1.08 mm., average 0.96 mm.; specimens deposited in U. S. National Museum No. 92743.

Male.—Body more slender and less oval than in female (Figs. 4, 5). Genital segment rounded and quite pronouncedly swollen. The anal segment is longer than either of the two preceding segments. The first antennae are twice geniculated (Fig. 6). The segmentation is not clear, but there appears to be about 14 segments. The end segment is shorter than the penultimate. The natatory legs are as in the female. The fifth legs are as in the female but the inner spine of the free segment is longer and more seta-like. The sixth legs are each represented by three well-developed setae.

Length including caudal rami: 0.72-0.78 mm., average 0.75 mm.; specimens deposited in U. S. National Museum No. 92743.

Nauplius.—The nauplius is characteristically cyclopoid especially with



Figs. 7-18. *Cyclops dimorphus*—7. Female-first leg; 8. Female-second leg; 9. Female-third leg; 10. Female-fifth leg; 11. Female-fourth leg; 12. Female-second antenna; 13. Female-first maxilliped; 14. Female-second maxilliped; 15. Female-mandibular blade; 16. Nauplius larva-ventral; 17. Nauplius larva last stage-ventral; 18. Nauplius larva, mandible.

respect to the mandibular structure (Figs. 16-18). In the last stage the body is oval with the greatest width anterior to the middle. There is no constriction at the posterior end as shown by Gurney (1933) for *C. gracilis* but the caudal armature is similar to that species in that each ramus has a strong apical seta flanked on the outside by a pair of shorter, lighter setae. This differs from the caudal structure of *C. bicolor* as given by Ewers (1930) and for *C. minutus* by Gurney (1933) where the apical setae are very weak.

Remarks.—The Salton Sea species is allied to *C. bicolor* but it differs from that species particularly in the structure of the fifth and sixth legs and in the absence of a small outer terminal spine on the distal endopod segment of the fourth leg. It differs also in the structural features from the closely related *C. rubellus* and *C. varicans* from which it differs also in the fewer number of segments in the first antenna and in the more slender caudal rami. There are some similarities also to *C. minutus* and *C. gracilis* but it differs from these species notably in the presence of a long inner spine on the second basis of the first leg, in the structure of the fifth legs, and in the structure of the nauplius larvae. It resembles *C. panamensis* Marsh in general form of the female fifth legs but it is distinct from that species especially by its more robust body and by the proportional lengths of the caudal rami and the abdominal segments. In *C. panamensis* the rami are somewhat shorter than the last two abdominal segments.

C. dimorphus is the only species of cyclopoid found in collections made on the following dates in the Salton Sea: Oct. 29, 1944—Desert Beach; May 13, 1945—Desert Beach; Jan. 5, 1946—Desert Beach; Dec. 30, 1946—Sea Plane Base, Westmorland; June 22, 1947—Desert Beach; April 29, 1949—Sea Plane Base, Westmorland; Dec. 28, 1949—Sea Plane Base, Westmorland.

It was especially abundant in the October 1944 collection when many females carried a pair of egg sacs each with 12 to 16 eggs. In the other collections it was common except for May 13, 1945 when it was rare.

The salinity of Salton Sea at the above dates and locations ranged from 27.81 to 28.40 parts per thousand.

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ON THE GEOPHYSICAL INTERPRETATION OF IRREGULARITIES IN THE ROTATION OF THE EARTH*

Walter Munk and Roger Revelle

(Received 1952 May 20)

Summary

Astronomical observations have indicated that variations in the Earth's rotation by several parts per hundred million sometimes occur over periods of one or two decades. These irregularities may be caused by variations in the distribution of matter, or by variable motion relative to the Earth. It is found that processes in the atmosphere and ocean are inadequate to account for all of the observed irregularities, but that their effect is not necessarily negligible. Processes in the crust and mantle could barely do so, but such processes seem highly unlikely for a number of reasons. The irregularities can be accounted for by a variable motion in the core amounting to a fraction of the total motion indicated by the westward drift of the Earth's magnetic field.

1. *Introduction.*—Almost fifty years ago Newcomb first noted the existence of irregularities in the rate of rotation of the Earth.† The evidence now consists of irregularities in the longitudes of the Sun, Moon, Mercury and Venus, and of eclipses of Jupiter's satellites. The irregularities are surprisingly large, and they have been thought to occur rather suddenly, with the last three important changes near 1860, 1900 and 1920. Accordingly, investigators have searched for suitable catastrophic events at these times. None seems to have been forthcoming.

A recent analysis by Brouwer‡ makes the catastrophic hypothesis much less attractive. In fact, the observations do not differ in any convincing way from what might be expected from a *random* variation in the angular velocity of the Earth. If this is so, adequate causes of random character must be sought for, rather than intermittent catastrophic events. Because of the nature of the observational material we are concerned here with causes that are effective over times larger than years but shorter than centuries.

The magnitude of the random variations can be expressed, for example, by the root-mean-square (rms) deviation over the past 100 years in the annual average of the length of day. For the interval 1860–1950, we find this to be 1·6 milliseconds, or two parts in a hundred million. According to Brouwer‡ the largest single deviation from the mean, 5·5 ms, occurred in the early 1860s.

During the same time interval the mean annual pole of instantaneous rotation has moved by less than 15 ft. This follows from precise measurements conducted by the International Latitude Service. It will be shown that the relative stability

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* Contribution No. 590 in the Scripps Series. This work has been supported by the Office of Naval Research and by a Grant-in-Aid from the Institute of Geophysics of the University of California.

† The reader is referred to a summary by Sir Harold Spencer Jones, " The Measurement of Time ", *Endeavour*, 4, 123–130, 1945. A very readable popular account of the subject has been given by R. S. Richardson in *Astounding Science Fiction* (New York), 44, 3, 110–121, 1949.

‡ D. Brouwer, " A New Discussion of the Changes in the Earth's Rate of Rotation ", *Proc. Nat. Acad. Sci.*, **38**, 1–12, 1952.

of the pole of rotation, as compared to the variations in the rate of rotation, provides a powerful tool in discussing possible causes.

In subsequent sections we shall look for possible causes in the atmosphere, oceans, crust, mantle and core of the Earth. In each case the causes may be of two types: those arising from displacement of matter, and hence affecting the inertia of the system; and those arising from motion, and affecting the angular velocity.

2. *The atmosphere.*—Perhaps the most obvious place to look for an explanation is the atmosphere. The rms deviation of 1·6 ms happens to be nearly twice the amplitude of the annual variation, which is due, in part at least, to winds.* The seasonal variation in the distribution of air mass plays a relatively minor part.† It would therefore require decades of winter weather, followed by decades of summer weather to account for half the observed anomalies. This means that the major anomalies cannot be due to atmospheric conditions; it also implies that the effect of the atmosphere on these long-period anomalies is not altogether negligible.

To illustrate the last point, we note* that the winds from 20° N. to 90° N. account for three-fourths of the observed annual variation, but that there is cancellation in part by winds in the southern hemisphere. A change by 10 per cent in the circulation of the northern hemisphere alone would change the length of the day by 0·1 ms. If such conditions could persist for a few decades, they would account for somewhat less than 10 per cent of the observed anomalies.

3. *The oceans.*—The effect of ocean currents is negligible compared to the effect of winds, as considered above.† To consider the effect of changes in the distribution of matter, consider a rise in sea level over all oceans by z_w cm, resulting from a melting of ice over Greenland and Antarctica. This will have a two-fold effect on the Earth's rotation: the angular velocity will diminish, because of the increase in the moment of inertia; the axis of instantaneous rotation will be tilted, because of the asymmetrical distribution of land and sea.

The expressions for these effects are

$$k = \frac{\tau}{T} = \frac{9}{4\pi} \frac{\rho_w}{\rho_e} \frac{z_w}{a} \kappa D, \tag{1}$$

$$l = \frac{\lambda}{a} = -\frac{9}{4\pi} \frac{\rho_w}{\rho_e} \frac{z_w}{a} \Gamma \kappa F, \tag{2}$$

$$m = \frac{\mu}{a} = -\frac{9}{4\pi} \frac{\rho_w}{\rho_e} \frac{z_w}{a} \Gamma \kappa E, \tag{3}$$

where T is the length of the day and τ its variation; l, m the angles of tilt of the axis of instantaneous rotation towards Greenwich and 90° east of Greenwich, respectively, and λ, μ the corresponding displacements of the north pole of rotation; ρ_w is the density of water; ρ_e the mean density of the Earth and a its radius; Γ is the number of sidereal days in the Eulerian period (434), and it is assumed that the variation in sea level takes place over a time long compared to this period. The equation for k follows directly from conservation of angular momentum. The expressions for l, m follow from Jeffreys'‡ equations 13.2 (2) with $\dot{l} = \dot{m} = 0$.

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* Y. Mintz and W. Munk, "The Effect of Winds and Tides on the Length of the Day", *Tellus*, 3, 117–121, 1951.

† W. H. Munk and R. L. Miller, "Variations in the Earth's Angular Velocity Resulting from Fluctuations in Atmospheric and Oceanic Circulation", *Tellus*, 2, 93–101, 1950.

‡ Harold Jeffreys, *The Earth*, p. 239, London, 1929.

The coefficient κ allows for the elastic yielding in the Earth under the pressure of superficial matter.* No allowance has been made for plastic adjustments. These appear to involve "relaxation times" of several thousand years, and we are here concerned with changes over a few decades.

In order to take into account the removal of ice as well as the rise in sea level, the integrals

$$\left.\begin{aligned} C &= \iint \sin\theta \, d\theta \, d\phi, & D &= \iint \sin^3\theta \, d\theta \, d\phi, \\ E &= \iint \sin^2\theta \cos\theta \sin\phi \, d\theta \, d\phi, & F &= \iint \sin^2\theta \cos\theta \cos\phi \, d\theta \, d\phi, \end{aligned}\right\} \tag{4}$$

involving co-latitude θ and east longitude ϕ, will be required over certain specified portions of the Earth's surface (Table I). The integral

$$G = \iint \sin^5\theta \, d\theta \, d\phi \tag{5}$$

is included for later reference (Section 4.2). Suppose the antarctic ice-cap (density ρ_i) is lowered by z_i, the Greenland ice-cap by sz_i and the sea level rises by z_w. The mass of water added to the oceans must equal the mass of the melted ice, and therefore

$$\rho_w z_w C_o = \rho_i z_i C_a + \rho_i s z_i C_g. \tag{6}$$

TABLE I

Values of integrals over specified areas

	C	D	E	F	G
North-polar Sea	0·389	0·030	−0·008	0·022	0·001
Atlantic Ocean, north of 40° S.	1·651	1·299	−0·165	0·054	1·079
Pacific Ocean, north of 40° S.	3·593	2·984	0·170	−0·223	2·602
Indian Ocean, north of 40° S.	1·269	1·119	−0·207	−0·036	1·006
Antarctic Ocean, south of 40° S.	1·883	0·677	0·008	0·011	0·285
All oceans (subscript "*o*")	8·785	6·109	−0·202	−0·172	4·973
Antarctic Continent (subscript "*a*")	0·354	0·023	−0·020	−0·007	0·002
Greenland (subscript "*g*")	0·052	0·003	−0·010	0·011	0·000

Here C_o, C_a and C_g refer to the values of C in the last three lines in Table I. The calculations were made for three cases, $s=0$, $s=1$, $s=\infty$, corresponding to melting on Antarctica only, equal melting per unit area on Antarctica and Greenland, and melting on Greenland only. The ratio sC_g/C_a denotes the total contribution of melted water by Greenland compared to Antarctica.

We must now write

$$\rho_w z_w D_o - \rho_i z_i D_a - \rho_i s z_i D_g = \rho_w z_w D_o (1 - K_D) \tag{7}$$

for $\rho_w z_w D$ in equation (1), and similar expressions for $\rho_w z_w E$ and $\rho_w z_w F$. Equations (6) and (7) give

$$K_D = \frac{C_o}{C_a + sC_g} \, \frac{D_a + sD_g}{D_o},$$

and similar expressions for K_E and K_F. The K-factors allow for the effect of ice-caps. Numerical results are summarized in Table II, assuming $\kappa=0·6$, $\rho_w=1·0$, $\rho_e=5·5$. For example, a rise in sea level by 1 cm increases the day by 0·06 ms, and displaces the north pole of rotation by $\frac{1}{3}$ ft. toward Chicago, or by 2·8 ft. toward Greenland, according to whether the ice melts on Antarctica or Greenland. The pole of rotation is therefore a remarkably sensitive indicator of the source of melted water.

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* Harold Jeffreys, *loc. cit.*

If the observed fluctuations in the length of day by 1·6 ms are to be attributed to oscillations in sea level, this would entail several oscillations by something like 25 cm since 1850. Using the published values* for mean annual sea level at 132 tide-gauge stations all over the world, and combining near stations that show similar behaviour, we have computed the average sea level at 50 localities† for three consecutive decades, starting in 1901. The numerical values are tabulated in Appendix I. In Fig. 1 the average changes from the first to the second decade and from the second to the third decade have been plotted.

TABLE II

Effect of sea level rise z_w on length of day and tilt of axis, for melting on Antarctica only, Antarctica and Greenland, and Greenland only

s	0	1	∞
sC_g/C_a	0	0·15	∞
K_D	0·09	0·09	0·08
K_E	2·45	3·20	8·36
K_F	1·01	−0·50	−10·80
τ/z_w in millisec per cm	0·059	0·059	0·060
l/z_w in 0″·01 per cm, or λ/z in ft. per cm‡	0·00	0·28	2·22
m/z_w in 0″·01 per cm, or μ/z in ft. per cm	−0·32	−0·49	−1·63

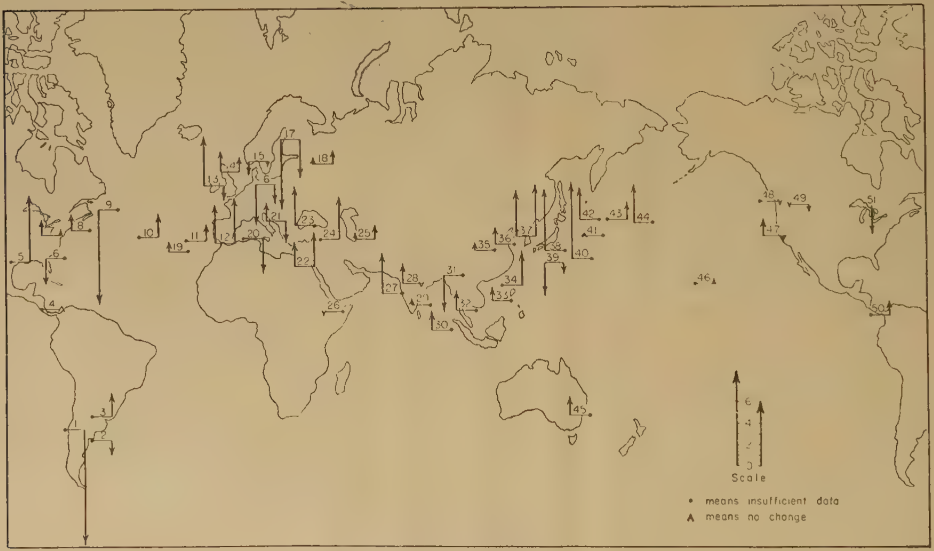

FIG. 1.—*Changes in recorded sea level in centimetres per decade. Left arrow: change between mean sea level during decade 1901–10 and mean sea level during decade 1911–20; right arrow: changes between 1911–20 and 1921–30. Arrows are located at latitudes of recording stations, but not necessarily at correct longitude. For location refer to corresponding group number in Appendix I.*

Changes by as much as 5 cm per decade are not uncommon, but they differ in direction from one location to the next, and the values are surprisingly variable with regard to time. Some of the variability is due to meteorological factors. A large part of the recorded changes must be due to crustal movement. What part, if any, is due to a world-wide change in sea level cannot be told from this abbreviated analysis, and it is not certain whether the most careful analysis can yield results comfortably above the "noise level" of the observations. Any eustatic change certainly cannot exceed 10 cm.

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* Association d'Océanographie Physique, Union Géodesique et Géophysique Internationale, *Publ. Sci.* No. 5, *Monthly and Annual Mean Heights of Sea Level up to and including the year* 1936, 252 pp., 1940.

† Group 51 in the Great Lakes region constitutes a special case (see Appendix I).

‡ A tilt by 0″·01 in the axis of instantaneous rotation corresponds very nearly to a displacement by 1 ft. of the north pole of rotation with respect to the surface of the Earth.

Observed changes in sea level may be due to heating or cooling of the ocean water. A heating by 1 deg. C of the entire oceans would raise the sea level by 60 cm! This part of the changes in sea level can be neglected as far as the effect on the Earth's rotation is concerned.* We shall overestimate the effect of changes in sea level if we attribute them entirely to melting or freezing at high latitudes, and neglect isostatic adjustment. Hence the maximum possible eustatic change in sea level from 1910 to 1930 cannot have changed the length of day by more than 0·6 ms; the observed decrease† equals 3·8 ms, and would imply a lowering in sea level by 63 cm! The recorded changes in sea level can account for but a fraction of the recorded changes in the length of day.

The same conclusion is reached by an argument which circumvents the problems of thermal expansion and possible isostatic adjustment. By dividing the ratios in the last three lines of Table II we obtain

$s =$	0	1	∞
λ/τ in ft./ms $=$	0·0	4·7	37
μ/τ in ft./ms $=$	$-5·3$	$-8·2$	-27

depending on the source of melted water. A value of $\tau = -3·8$ ms between 1910–1930 implies a corresponding displacement of the pole of rotation by 20 ft. toward western Siberia, or 37 ft. toward central Siberia, or 175 ft. toward eastern Siberia. Astronomical evidence in this regard is not reliable, but the indication is for a movement of the "mean" pole by 10 ft. toward Greenland (away from Siberia) between 1900 and 1925‡, and very little movement thereafter.§ Such evidence as exists is therefore opposed to the sea-level hypothesis. The present argument has the advantage of leading from one astronomical observation to another, making use of the Earth's sciences only with regard to the distribution of land and sea, and the location of Greenland.

We conclude, as we did in the case of possible atmospheric factors, that variations in sea level cannot account for the major variations in the length of day, but that the effect is not necessarily negligible. We cannot, however, exclude the possibility that the reported displacement of the pole of rotation may have been caused by a rise in sea level of a few centimetres during the last fifty years, nor that a secular change in the length of the day since Egyptian times may have been the result of a eustatic drop in sea level by a few metres during the last few thousand years.*

4. *The Earth's crust and mantle*

4.1. *Turbulence of continents.*—Let us consider for the moment that vertical movements of continents are associated with an appropriate divergence in the horizontal plastic flow of the Earth's mantle. Neglect elastic yield. Later we can allow for the numerical factors that enter when this hypothesis is varied. We shall also assume that the sea level does not vary because of changes in the volume of sea water, so that long-period variations on tide-gauge records are solely an indication of crustal movements.

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* W. H. Munk and R. R. Revelle, "Sea Level and the Rotation of the Earth", *Am. J. Sci.* (in press).

† D. Brouwer, *loc. cit.*

‡ B. Wanach, "Eine fortschreitende Lagenänderung der Erdachse", *Zeitschr. f. Geoph.*, **3**, 102–105, 1927.

§ W. Markowitz, "The Free Polar Motions, 1916.0–1940.0", *Astr. J.*, **50**, 17–21, 1942.

Suppose the Earth's surface is cut into n blocks, each moving as a unit. Over the Earth as a whole, as much mass must go up as goes down, but the tensor of inertia will fluctuate, since the mean latitude and longitude of the rising blocks will not, in general, equal those of the sinking blocks. We shall compute the random variations in the length of day and position of the pole of rotation induced by random movements of these blocks. For each block, let A, θ and z designate area, co-latitude and change in elevation above mean sea level. Because of conservation of mass, $\Delta M = \sum_i A_i z_i = 0$, so that

$$\langle \Delta M^2 \rangle = \sum_i A_i^2 \langle z_i^2 \rangle + \sum_{i \neq j}\sum A_i A_j \langle z_i z_j \rangle = 0,$$

where the summations are from $i=1$ to $i=n$, and $\langle\ \rangle$ designates a mean value. Let us assume each block has the same rms change in elevation, $\langle z_i^2 \rangle = \bar{z}^2$. Let $r = \langle z_i z_j \rangle / \bar{z}^2$ designate the correlation between the elevation of one block and any other. If there is no tendency for neighbouring blocks to move together, r will be independent of i and j. The above equation then becomes

$$\langle \Delta M^2 \rangle = (\sum_i A_i^2 + r \sum_{i \neq j}\sum A_i A_j) \bar{z}^2 = 0.$$

The resulting anomaly in the moment of inertia is $\Delta I = \sum_i B_i z_i$, where

$$B_i = (\rho_r a^2) A_i \sin^2 \theta_i$$

and ρ_r is the density of crustal rocks. Then

$$\langle \Delta I^2 \rangle = (\sum_i B_i^2 + r \sum_{i \neq j}\sum B_i B_j) \bar{z}^2.$$

The elimination of r between the last two equations yields the desired result.

Suppose there are n blocks of equal area A. Then

$$\sum A_i^2 = nA^2, \quad \sum_{i \neq j}\sum A_i A_j = n(n-1)A^2 \quad \text{and} \quad r = -(n-1)^{-1}.$$

Furthermore

$$B_i^2 = (\rho_r a^2)^2 A^2 \sum \sin^4 \theta_i = (\rho_r a^2)^2 A^2 n(\tfrac{8}{15}), \qquad \sum_{i \neq j}\sum B_i B_j = (\rho_r a^2)^2 A^2 n(n-1)(\tfrac{2}{3})^2.$$

This leads to

$$k = \frac{\bar{\tau}}{T} = \frac{\overline{\Delta I}}{I} = \frac{6}{\sqrt{5}} \frac{\rho_r}{\rho_e} \frac{\bar{z}}{a} n^{-1/2}, \tag{8}$$

where the bars designate rms values and I is the Earth's moment of inertia. In a similar way, we find

$$\bar{l}, \bar{m} = 3\sqrt{\left(\frac{3}{5}\right)}\, \Gamma \frac{\rho_r}{\rho_e} \frac{\bar{z}}{a} n^{-1/2}. \tag{9}$$

With $\rho_r = 2{\cdot}75\ \text{g cm}^{-3}$, $\rho_e = 5{\cdot}5\ \text{g cm}^{-3}$, $\Gamma = 434$, this gives $\bar{\tau}/\bar{z} = 0{\cdot}18 n^{-1/2}$ ms/cm, $\bar{\lambda}/\bar{z} = \bar{\mu}/\bar{z} = 16\, n^{-1/2}$ ft./cm. In these calculations $n \gg 1$.

First we note that for any value of n, λ or μ in feet is a hundred times τ in milliseconds. Thus if τ is 1·6 ms, the rms displacement of the pole over the last few centuries should be 160 ft. We have observations only since 1890, and they indicate displacements by 15 ft. at most. During this interval τ was more than twice its rms value. This evidence is, of course, statistically inadequate, as several hundred years of observations are required before a meaningful comparison of $\bar{\tau}$ with $\bar{\lambda}$, $\bar{\mu}$ can be made. Under the circumstances, we have permitted ourselves to present preliminary results at this time. The results do not support the hypothesis that changes in the length of day are caused by random crustal movement.

Next assume $n = 21$, corresponding to blocks the size of North America. If $\tau = 1{\cdot}6$ ms, then $z = 40$ cm. In certain areas, notably Scandinavia and the Great Lakes region and possibly northern France, vertical movements of this order have taken place over a period of decades.* But over areas as large as North America, the average movements cannot be in excess of a few centimetres in several decades. We conclude that a random turbulence of large crustal blocks could account for movements of the mean pole by 10 ft. or so, but cannot account for the observed irregularities in the length of the day.

4.2. *Organized crustal movement.*—We shall consider a better organized motion of the crust. Clearly the most effective motion would be a crustal rise, z, in high latitudes, and a corresponding sinking at low latitudes. As before, we neglect elastic yield and write

$$k = \frac{\tau}{T} = \frac{9}{4\pi}\frac{\rho_r}{\rho_e}\frac{1}{a}\int_0^{2\pi}\int_0^{\pi} z \sin^3\theta \, d\theta \, d\phi.$$

TABLE III

Changes in absolute sea level z_w (cm) and recorded sea level z_T (cm) resulting from a crustal movement $z = c\,(1 - 1{\cdot}5 \sin^2\theta)$ before elastic yield. The values of c (cm) correspond to a decrease by 3·8 ms in the length of day, as indicated by astronomical observations for the period 1910–30

	c	z_w	z_T at stated co-latitudes			
			0°	30°	60°	90°
inelastic	42	0	−42	−30	6	23
elastic	137	−5·5	−122	−79	9	53

If z is expanded into tesseral harmonics, z_n, the only term for which this integral does not vanish is

$$z_2 = c(1 - \tfrac{3}{2}\sin^2\theta). \tag{10}$$

This component varies from $+c$ at the poles to $-\frac{1}{2}c$ at the equator, and vanishes at co-latitude $\theta_1 = \arccos(1/\sqrt{3}) = 54^\circ\,40'$. Upon substitution, we obtain

$$k = -\frac{6}{5}\frac{\rho_r}{\rho_e}\frac{c}{a}, \tag{11}$$

or $\tau/c = -0{\cdot}08$ ms/cm. Numerical values corresponding to conditions during the first few decades of this century are give in Table III. What is involved here is an apparent rise in sea level as recorded on tide gauges ($z_T = -z$) by 6 cm near co-latitude 60°, where most stations are located; a larger rise near the equator and an even larger lowering at high latitudes.

These values cannot be ruled out on the basis of existing tide-gauge data. It therefore seems worth while to derive the somewhat intricate corrections resulting from elastic yield of the Earth, and such changes in sea level as are brought about by movements of the ocean bottom. Suppose that by (plastic) transfer of matter from one region to another, the load per unit surface is varied by some amount $\sigma(\mathrm{g\,cm^{-2}})$. Conservation of mass requires that

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* J. Gilluly, "Distribution of Mountain Building in Geologic Times", *Bull. Geol. Soc. Am.*, **60**, 561–90, 1949. B. Gutenberg, "Changes in Sea Level, Postglacial Uplift, and Mobility of the Earth's Interior", *Bull. Geol. Soc. Am.*, **52**, 721–772, 1941.

$$\iint_l \sigma(\theta, \phi) \sin\theta \, d\theta \, d\phi = 0, \tag{12}$$

with the integral taken over all of the Earth's surface. The elastic yield will have two consequences: (1) the moment of inertia, and hence k will be reduced by a factor κ from what it would be on an inelastic Earth; (2) the Earth's surface will yield by $-\epsilon\sigma$. Rosenhead* has derived the formulae for κ and ϵ†, taking into account the internal constitution of the Earth. If σ is expanded in surface harmonics, σ_n, values pertaining to σ_2 are $\kappa = 0{\cdot}6$, $\epsilon = 0{\cdot}062\ \mathrm{cm^3\,g^{-1}}$.

Let ρ be the density of crustal rocks, ρ_w the density of sea water and $\Delta\rho = \rho_r - \rho_w$. The elastic yield is then $-\epsilon\rho_r z$ on land and $-\epsilon\Delta\rho z$ due to matter being added on the sea bottom.

Next we must allow for changes in sea level due to vertical movements of the sea bottom. The water mass per unit area displaced by the sea bottom is $\rho_w z(1 - \epsilon\Delta\rho)$. The corresponding rise in sea level, z_w, is then given by

$$a^2 C z_w = a^2 \iint_0 z(1 - \epsilon\Delta\rho) \sin\theta \, d\theta \, d\phi, \tag{13}$$

where C is the integral defined in equation (4), and a^2C the surface area of all oceans.

The variation in load per unit surface area, due to both rock and water, is

$$\sigma = \rho_r z \tag{14a}$$

over land and

$$\sigma = \rho_r z + \rho_w [z_w - z(1 - \epsilon\Delta\rho)] \tag{14b}$$

over water. In calculating the effect of this surface load on the Earth's rotation, all that has to be done is to write $\kappa\sigma$ instead of σ, and then to compute the effect as if the Earth were inelastic:

$$\begin{aligned} k &= \frac{9}{4\pi} \frac{1}{\rho_e a} \kappa \iint_l \sigma \sin^3\theta \, d\theta \, d\phi \\ &= \frac{9\kappa}{4\pi\rho_e a} \left\{ \rho_r \iint_l z \sin^3\theta \, d\theta \, d\phi + \rho_w z_w \iint_0 \sin^3\theta \, d\theta \, d\phi - \rho_w (1 - \epsilon\Delta\rho) \iint_0 z \sin^3\theta \, d\theta \, d\phi \right\} \\ &= -\frac{6}{5} \frac{\rho_r}{\rho_e} \frac{c}{a} \kappa \left\{ 1 + \frac{45}{16\pi} \frac{\rho_w}{\rho_r} (1 - \epsilon\Delta\rho) \left(\frac{D^2}{C} - G \right) \right\}, \end{aligned} \tag{15}$$

with C, D and G the integrals defined in equations (4) and (5). With the numerical values in Table I, $\tau/c = -0{\cdot}028$ ms/cm, as compared to $-0{\cdot}080$ ms/cm for the inelastic Earth. Since D^2 nearly equals CG, the numerical value is quite uncertain, and may vary by a factor of two.

Equation (10) with c replaced by $(1 - \rho_r \epsilon)c$ gives the expression for the crustal movement relative to the centre of the Earth. What is actually needed is the movement relative to sea level, i.e. the recorded sea level z_T. A rise in sea level induces an elastic yield of the sea bottom. The rigorous procedure for computing this yield is to expand into surface harmonics S_n, a function which is unity over the ocean and zero over land, and compute ϵ_n for each component from Rosenhead's general theory. Then by summing $\epsilon_n S_n(\theta, \phi)$ the yield at any point θ, ϕ can be computed. Such a calculation would be tedious. Since the effect is small, we shall set $\epsilon_n = \epsilon_2 = \epsilon$, and write simply $-\epsilon\rho_w z_w$ for the elastic yield of the sea bottom due to changes in sea level.

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* L. Rosenhead, "The annual variation of latitude", *M.N., Geophys. Suppl.*, **2**, 140–170, 1929.

† Rosenhead's q/a, equation (115).

The combined vertical changes relative to the centre of the Earth are:

$$\begin{array}{ll} \text{Continent} & z(1-\epsilon\rho_r), \\ \text{Sea level} & z_w(1-\epsilon\rho_w), \\ \text{Sea bottom} & z(1-\epsilon\Delta\rho) - z_w\epsilon\rho_w. \end{array}$$

We note that

$$\text{Sea level} - \text{Continent} \;= z_w - z + \epsilon(z\rho_r - z_w\rho_w)$$

and

$$\text{Sea level} - \text{Sea bottom} = z_w - z + \epsilon(z\rho_r - z\rho_w)$$

differ by a small quantity, $\epsilon(z_w - z)\rho_w$. This would involve a discontinuity at the coastline. We shall assume that z_T, the *recorded* sea level on tide-gauges, lies midway between the two values:

$$z_T = z_w - z + \epsilon[z\rho_r - \tfrac{1}{2}(z + z_w)\rho_w]. \tag{16}$$

Using the definition in equation (4) and the numerical values in Table I, we obtain

$$z_w = (1-\epsilon\Delta\rho)\left(1 - \frac{3}{2}\frac{D}{C}\right)c = -0{\cdot}04c \tag{17}$$

according to equation (13), and

$$z_T = \tfrac{3}{2}(1 - \epsilon\rho_r + \tfrac{1}{2}\epsilon\rho_w)c\left(\sin^2\theta - \frac{D}{C}\right) = 1{\cdot}29c(\sin^2\theta - 0{\cdot}695) \tag{18}$$

according to (16). The negative sign and small value of z_w/c simply mean that there is more, but only slightly more, ocean surface at low latitudes, where the crustal movement varies like $-c$, than at high latitudes, where it varies like $+c$. This change in sea level will cause a tilting in the axis of rotation. The amount can be found by substituting for z_w from (17) into (2) and (3):

$$\lambda/c = -0{\cdot}008\,\text{ft./cm}, \quad \mu/c = -0{\cdot}009\,\text{ft./cm}. \tag{19}$$

This tilt does not result directly from the crustal movement, which has been assumed independent of longitude (equation 10), but indirectly from the change in sea level which is induced by the crustal movement.

Numerical values are given in the second line of Table III. They may be in error by a factor of two, since they depend on the combinations $D^2 - CG$ (equation 15) and $2C - 3D$ (equation 17), both of which are small differences of nearly equal numbers. The change in the length of day between 1910 and 1930, to which they correspond, is one of the largest on record. The required changes in recorded sea level in temperate latitudes amount to a few inches in several decades, and such changes are the rule rather than the exception. Near the equator and at high latitudes the required changes are abnormally large. The associated displacement of the pole of rotation follows from equation (19). It amounts to less than a foot, and is therefore not detectable.

A second difficulty arises from the fact that the length of day has both increased and decreased, and accordingly changes in recorded sea level would also have to change sign. Most of our discussion has dealt with the decrease by 3·8 ms in the length of day between 1910 and 1930. Between 1890 and 1900 the length of day increased by about the same amount*, and this would require a sinking of the crust at high latitude, and a rise of the equatorial region. Aside from the *apriori* unlikelihood of a rapid reversal of such a large-scale phenomenon, there is no evidence for a universal change in trend of tide records at the turn of the century. However, the few stations that were then in operation were all located at co-latitudes 50° to 60°, where the evidence is not decisive. Also, long-term tide records often do reveal large changes, and even reversals, of trends over a period of several decades.†

Finally, we consider the north–south motion of matter in the mantle associated with the assumed vertical motion of the crust. Let h be the thickness of the layer in which horizontal motion takes place, and x the mean northward displacement in this layer. Then

$$x = \frac{1}{4}\frac{a}{h} c \sin 2\theta. \tag{20}$$

The maximum displacement is at 45° latitudes. For $c = 137$ cm and $h/a = 0{\cdot}1$, corresponding to the greatest depths of earthquakes, this gives $x = 342$ cm, or 17 cm/year. For comparison, thermal convection currents in the mantle have been estimated by Pekeris‡ to be of the order of 1 cm/year. The velocity of subcrustal flow into Fennoscandia corresponding to the observed rise of this area is also of the order of 1 cm/year. The angular momentum of this flow is altogether negligible, as will be shown in the next section dealing with the effect of variable motion in the core.

5. *The Earth's core.*—Finally, we may mention the boundary of the Earth's core as a possible seat of the variations. Since the effect varies as the fourth power of the distance from the centre, and is proportional to the density difference at the boundary, we find the effect there to be reduced by the factor

$$(0{\cdot}55)^4 \frac{10{\cdot}1 - 5{\cdot}4}{2{\cdot}75} = \frac{1}{6{\cdot}3}.$$

The required amplitudes of vertical displacement at the core are about six times those at the Earth's surface.

Variable motion within the fluid core has been suggested by Slichter § as a possible cause for the irregularities in the Earth's rotation. This hypothesis was ruled out by Bullard || because his computations lead him to believe that the electromagnetic coupling between core and mantle (viscous coupling is negligible) has a time constant t of the order of 300 years, "....whilst the observed changes sometimes occur in a few years". But Brouwer's analysis has removed much of the argument for sudden changes, indicating rather that marked changes in angular velocity take place in a few decades. Furthermore, the time constant t varies inversely with the electric conductivity of the mantle, and this quantity, according to Bullard, is "only vaguely known". Under the circumstances this hypothesis cannot be dismissed without some further calculations.

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[*] D. Brouwer, *loc. cit.*

[†] B. Gutenberg, *loc. cit.* H. A. Marmer, "Is the Atlantic Coast Sinking? The Evidence from the Tide", *Geogr. Rev.*, **38**, 652–657, 1948.

[‡] C. L. Pekeris, "Thermal convection in the Interior of the Earth", *M.N., Geophys. Suppl.*, **3**, 343–367, 1935.

[§] Personal communication.

[||] E. C. Bullard, C. Freedman, H. Gellman and J. Nixon, "The westward drift of the Earth's magnetic field", *Phil. Trans.* A, **243**, 67–92, 1950.

Bullard considers the simple case of an inner and outer portion of the fluid core, with radii b_1 and b_2, and uniform angular velocities ω_1 and ω_2, respectively. Thermal convection due to radioactive heating causes a flux of matter between the inner and outer parts of the core. The resulting flux of angular momentum will tend to make the inner core rotate somewhat faster, and the outer core somewhat slower, than the Earth as a whole. Features in the outer core will then move westward relative to the mantle. This, briefly, is Bullard's explanation for the westward drift of the Earth's magnetic field.

Suppose that initially the angular velocities of the core, ω_1 and ω_2, and of the mantle, ω_m, are so related that the electromagnetic couple between core and mantle is zero. Thereupon the angular velocities in the core vary by $\Delta\omega_1$ and $\Delta\omega_2$ because of a change in convection. The resulting electromagnetic couple will change the angular velocity of the mantle by $\Delta\omega_m$, until, after a time of the order t, the torque again vanishes, and*

$$\Delta\omega_m = \alpha^5\Delta\omega_1 + (1-\alpha^5)\Delta\omega_2 \quad \text{for a constant field,} \tag{21a}$$

$$\Delta\omega_m = \alpha^2\Delta\omega_1 + (1-\alpha^2)\Delta\omega_2 \quad \text{for a dipole field,} \tag{21b}$$

where $\alpha = b_1/b_2$. Conservation of angular momentum requires

$$I_1\Delta\omega_1 + I_2\Delta\omega_2 + I_m\Delta\omega_m = 0. \tag{22}$$

Equations (21) and (22) give, after some algebra,

$$\Delta\omega_m = 0 \qquad \text{for the constant field,} \tag{23a}$$

$$\Delta\omega_m = \frac{1-\alpha^3}{1+R(\beta^5-1)}\Delta(\omega_m-\omega_2) \quad \text{for the dipole,} \tag{23b}$$

where $\beta = a/b_2 = 1{\cdot}82$, $R = \rho_m/\rho_c$, and $\rho_m = 4{\cdot}3\,\mathrm{g\,cm^{-3}}$, $\rho_c = 12{\cdot}0\,\mathrm{g\,cm^{-3}}$ are the appropriate densities of the mantle and core.

Under the present hypothesis, equation (23*b*) relates measurements at astronomical observatories to those at magnetic observatories. With the astronomical observatories anchored to the mantle, the observed changes in the length of day are $\tau = -(T^2/2\pi)\Delta\omega_m$; and according to Bullard's hypothesis, the change in the westward drift of the Earth's magnetic field equals $\Delta(wd) = \Delta(\omega_m - \omega_2)$. For the dipole field, after a time of the order t,

$$\frac{\tau}{\Delta(wd)} = -\frac{T^2(1-\alpha^3)}{2\pi[1+R(\beta^5-1)]} = \frac{-8{\cdot}2\,(1-\alpha^3)\ \text{millisec}}{\text{degrees per decade}}. \tag{24}$$

Bullard finds $wd = 1^\circ{\cdot}80 \pm 0^\circ{\cdot}15$ per decade. Suppose $\Delta(wd) = 0^\circ{\cdot}15$ per decade, and $b_1 \leqslant \frac{1}{2}b_2$, so that $(1-\alpha^3) \approx 1$. This gives $\tau = 1{\cdot}2$ ms. Astronomical evidence gave a rms value of $\tau = 1{\cdot}6$ ms. The values are close enough to be interesting.

Between 1890 and 1910 the length of day increased by 3·6 ms, and between 1910 and 1930 it decreased by a similar amount. According to (24) this would call for a decrease in the westward drift by 0°·44 per decade between 1890 and 1910, and a similar increase between 1910 and 1930. When we derived these numerical relationships we did not realize that the magnetic data were good enough to study possible *variations* in the westward drift. At the 1952 May meeting of the American Geophysical Union, Vestine presented a curve showing variations in the westward drift since 1890. The curve resembles Brouwer's curve for the variation in the length of day; the changes are in the direction indicated above, and their magnitude is about three times as large. A factor of three can probably be gained by considering a different model from the simple two-layer core; or by assuming the constant field to be twice as large as the dipole field; or by setting $\alpha^3 = \frac{2}{3}$ in equation (24); or by assuming a time constant of electromagnetic coupling of fifty years, so that $1 - \exp(-\frac{20}{50}) = \frac{1}{3}$. The latter alternative leads to an electric conductivity in the mantle of 6×10^{-10} e.m.u., a value six times as large as that selected by Bullard, but not incompatible with present knowledge.

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* Bullard *et al., loc. cit.*

The velocities involved are of the order of 10 km per year at the core at the equator. In the preceding section we were concerned with velocities in the mantle amounting to 10 cm per year. Hence any variation in the angular momentum of the mantle must be negligible.

It would be desirable to consider the variations in latitude induced by a non-symmetrical circulation in the core, taking into account the appropriate electromagnetic couples. Vestine has in fact pointed out the existence at certain longitudes of northward and southward drifts in the magnetic field. Under the questionable assumption that the inner and outer core have a *common* axis of rotation so inclined as to account for Vestine's observations, we find the computed displacements of the pole of rotation to be an order of magnitude larger than observations of latitude would permit.

6. *Conclusions.*—Astronomical measurements over the last 300 years have revealed fluctuations in the annual average of the angular velocity of the Earth. Variations in the length of day by several milliseconds have occurred over periods of a few decades. It used to be thought that these changes occurred much more abruptly, and accordingly past investigations have searched for catastrophic causes. This limitation has been removed by the recent work of Brouwer, who has shown that the observed changes in the length of day can be fitted to a cumulative random series.

Unless these changes in the length of day are caused by disturbances which are quite symmetrical about the Earth's axis of rotation, there will also result a tilt in the axis of rotation. Observations of the International Latitude Service indicate that apart from an annual and a fourteen-month free motion, the pole of rotation has not moved by more than 15 ft. between 1890 and 1950. During the same period the length of day has fluctuated by nearly 5 ms. We have shown that these numerical values are consistent only with a nearly symmetrical disturbance.

With this limitation in mind, we have examined various processes in the atmosphere, oceans and lithosphere which might account for the observed fluctuations in the length of day. Possible causes fall into two categories: those due to changes in the moment of inertia because of changes in the distribution of matter; and those due to a variable motion relative to the Earth's crust. The results of this examination are as follows:

Section 2.—Variations in the distribution of air mass are completely inadequate to account for the observed fluctuation in the length of day. Long-term variation in the zonal circulation of the atmosphere might conceivably account for 5 to 10 per cent of the observed fluctuations.

Section 3.—Variations in oceanic circulation have a negligible effect. Changes in the volume of water in the oceans resulting from growth or melting of ice-caps and glaciers are a possible cause, but tide-gauge records indicate that not more than

20 per cent of the observed fluctuations in the length of day can be accounted for in this manner. Moreover, because of the asymmetry in the distribution of land and sea, changes in sea level large enough to account for the fluctuations in the length of day would be accompanied by displacements in the pole of rotation far too large and in a direction opposite to that indicated by the latitude observations.

Section 4.1.—Random fluctuations in the elevation of continental blocks of the Earth's crust, if sufficiently large to cause observed changes in the length of day, would likewise bring about displacements in the pole of rotation far greater than those observed from 1890 to 1950. Available evidence from tide-gauges suggests that oscillation in the elevation of crustal blocks have been less than 10 per cent of the amount required to account for the observed fluctuations in the length of day.

Section 4.2.—A symmetrical oscillation of the crust can be postulated, with a rise or fall in high latitudes, accompanied by a movement in the opposite sense in low latitudes. For a rigid Earth the required amplitudes cannot be ruled out on the basis of tide-gauges (nearly all of which are at latitudes where the vertical crustal movement would be small). However, when allowance is made for elastic yield and the mobility of ocean water, the required amplitudes are larger, but not much larger, than tide-gauge records indicate. The required velocity of sub-crustal flow is about twenty times larger than has been supposed possible, or than is indicated by the observed isostatic rise of Fennoscandia. Moreover, it is difficult to conceive of any geophysical mechanism which should be responsible for a general poleward flux of mantle material for twenty years, and a reverse flux during the next twenty years.

Section 5.—Electromagnetic coupling of the mantle to a turbulent core could account for the observed fluctuations, provided the conductivity of the mantle is about 10^{-9} e.m.u. Using Bullard's model, we have derived a numerical relation between the fluctuations in the length of day (as measured from observatories anchored to the mantle) and the variations in the westward drift of the Earth's magnetic field. Vestine's calculation of the westward drift of the magnetic field between 1890 and 1950 shows the proper relationship, qualitatively and quantitatively, to Brouwer's calculations of the length of day over the same period.

In conclusion, an organized vertical crustal movement, even if *a priori* unlikely, cannot be altogether ruled out as a possible cause for the fluctuations in the length of day. This is true especially if we ascribe most of the motion to the Antarctic, where tide-gauge data are lacking. On the other hand, there is positive evidence for ascribing the fluctuations to variable motion in the Earth's core. The core has also the advantage of being even less accessible than the Antarctic.

We are indebted to Miss Elizabeth Strong for the compilations in Table I and the Appendix.

Institute of Geophysics and the Scripps Institution of Oceanography,
University of California :
1952 *May* 15.

APPENDIX I

Group No.	Station	Lat. ° ′	Long. ° ′	1901–10 to 1911–20 cm per decade	1911–20 to 1921–30 cm per decade	Remarks
1	Quequén, Arg.	38 35 S.	58 42 W.		−11·2	3 years' data incomplete.
2	Mar Del Plata, Arg.	38 03 S.	57 33 W.		−1·2	1 year's data missing. 2 years' data incomplete.
3	Buenos Aires, Arg.	34 36 S.	58 22 W.		+2·2	
4	Cristobal, C.Z.	9 21 N.	79 55 W.		0·0	
5	Galveston, U.S.	29 19 N.	94 47 W.		+6·3	
6	Fernandina, U.S.	30 41 N.	81 28 W.	−2·5		
7	Baltimore, U.S.	39 16 N.	76 35 W.	+1·5	+0·6	1 year's data missing. 1 year's data incomplete
8	Ft. Hamilton, U.S.	40 37 N.	74 02 W.	+1·6		
9	Quebec, Can.	46 49 N.	71 11 W.	−9·1		2 years' data missing.
10	Horta, Azores	38 32 N.	28 38 W.		+2·1	6 years' data incomplete.
11	Lagos, Port.	37 06 N.	8 40 W.		+1·6	6 years' data incomplete.
12	St. Jean de Luz, Fr.	43 24 N.	1 41 W.	+0·3		
	Biarritz, Fr.	43 29 N.	1 34 W.	+3·4	+0·5	2 years' data missing.
	La Pallice, Fr.	46 10 N.	1 13 W.		+8·2	1 year's data missing.
	Les Sables d'Olonne	46 30 N.	1 47 W.	+7·4	+3·5	2 years' data missing.
	Mean			+3·7	+4·1	
13	Camaret, Fr.	48 16 N.	4 36 W.	+4·9		
	Brest, Fr.	48 23 N.	4 29 W.	+7·8	−2·2	
	Cherbourg, Fr.	49 39 N.	1 37 W.	+2·4	−13·8	
	Vlissingen, Neth.	51 27 N.	3 36 E.	+1·8	+2·9	
	Zierikzee, Neth.	51 38 N.	3 55 E.	+7·3	−0·6	
	Brouwerhaven, Neth.	51 44 N.	3 54 E.	+3·2	+0·2	
	Hellevoetsluis, Neth.	51 49 N.	4 08 E.	+7·0	−0·6	
	Maasluis, Neth.	51 55 N.	4 15 E.	+5·3	−2·2	
	Hoek van Holland, Neth.	51 59 N.	4 07 E.	+3·4	+2·0	
	Ijmuiden, Neth.	52 28 N.	4 35 E.	+6·2	+0·9	
	Den Helder, Neth.	52 58 N.	4 45 E.	+4·0	−0·4	
	Mean			+4·8	−1·4	
14	Harlingen, Neth.	53 10 N.	5 25 E.	+3·9	+1·6	
	Delfzijl, Neth.	53 20 N.	6 56 E.	+6·0	+1·2	
	Bremerhaven, Ger.	53 33 N.	8 34 E.	+2·1	+2·5	
	Esbjerg, Den.	55 28 N.	8 27 E.	+2·4	+2·1	
	Hirtshal, Den.	57 36 N.	9 57 E.	+0·9	+0·1	4 years' data incomplete.
	Frederikhavn, Den.	57 26 N.	10 34 E.	+0·9	−1·2	
	Göteborg, Sw.	57 43 N.	11 58 E.	+1·6	0·0	
	Varberg, Sw.	57 06 N.	12 13 E.	+0·8	+1·1	
	Malmö, Sw.	55 37 N.	13 00 E.	+3·1		1 year's data missing.
	Ystad, Sw.	55 25 N.	13 49 E.	+2·2	+2·4	
	Kungsholm Fort, Sw.	56 06 N.	15 35 E.	+0·2	−0·8	
	Ventspils, Latv.	57 24 N.	21 33 E.	(+1·7	+1·2)	No data 1911–20. Difference between 1st and 3rd decades divided between two periods in same ratio as rest of group.
	Liepāja, Latv.	56 32 N.	20 59 E.	(+2·7	+1·9)	See note on Ventspils above.
	Memel, Ger.	55 43 N.	21 07 E.	+1·9		
	Pillau, Ger.	54 38 N.	19 54 E.	+1·7	+3·1	
	Stolpmünde, Ger.	54 35 N.	16 51 E.		+3·8	
	Swinemünde, Ger.	53 56 N.	14 17 E.	+2·0	+2·4	
	Arkona, Ger.	54 41 N.	13 26 E.	+3·2	−0·6	5 years' data incomplete.
	Warnemünde, Ger.	54 11 N.	12 05 E.	+2·0	+3·4	
	Wismar, Ger.	53 54 N.	11 28 E.	+1·5	+2·3	

Group No.	Station	Lat. ° ′	Long. ° ′	1901–10 to 1911–20 cm per decade	1911–20 to 1921–30 cm per decade	Remarks
	Travemünde, Ger.	53 58 N.	10 53 E.	+3·4	+3·7	1 year's data missing.
	Marionleuchte, Ger.	54 30 N.	11 15 E.	+1·0	+0·7	
	Gedser, Den.	54 34 N.	11 58 E.	+1·4	+2·3	
	Korsör, Den.	55 20 N.	11 08 E.	+0·8	+1·2	
	Köbenhavn, Den.	55 41 N.	12 36 E.	+1·5	+1·6	
	Hornbaek, Den.	56 06 N.	12 28 E.	+0·6	+2·2	2 years' data incomplete.
	Slipshavn, Den.	55 17 N.	10 50 E.	+2·7	+1·6	1 year's data incomplete.
	Fredericia, Den.	55 34 N.	9 46 E.	+3·5	−0·1	1 year's data incomplete.
	Aarhus, Den.	56 09 N.	10 13 E.	+1·1	+1·0	
	Mean			+2·0	+1·5	
15	Strömstad, Sw.	58 57 N.	11 11 E.	−2·1	−0·1	1 year's data incomplete.
	Smögen, Sw.	58 22 N.	11 13 E.		−1·3	
	Bäckevik, Sw.	58 22 N.	11 15 E.	−1·7		
	Västervik, Sw.	57 46 N.	16 39 E.	+0·1		
	Mem, Sw.	58 29 N.	16 25 E.	−1·4		
	Mean			−1·3	−0·7	
16	Landsort, Sw.	58 45 N.	17 52 E.	−2·9	−0·8	
	Nedre Södertälje, Sw.	59 12 N.	17 38 E.	−0·8	−2·4	
	Stockholm, Sw.	59 19 N.	18 05 E.	−3·7	−1·8	
	Nedre Stockholm, Sw.	59 19 N.	18 05 E.	−4·1	−1·1	
	Lyökki, Fin.	60 51 N.	21 11 E.	−5·7	−2·8	
	Lyprtti, Fin.	60 36 N.	21 14 E.	−5·0	−2·4	
	Jungfrusund, Fin.	59 57 N.	22 22 E.	−3·0	−0·6	
	Utö, Fin.	59 47 N.	21 22 E.	−3·3	−1·4	2 years' data incomplete.
	Russarö, Fin.	59 46 N.	22 57 E.	−2·8	−1·0	2 years' data incomplete.
	Daugāvgriva, Latv.	57 03 N.	24 02 E.	(−7·9	−3·2)	See note on Ventspils, Group 14.
	Mean			−3·9	−1·8	
17	Bjorn, Sw.	60 38 N.	17 58 E.	−5·6	−3·4	
	Nedre Gävle, Sw.	60 41 N.	17 10 E.	−6·7	−0·1	
	Draghällan, Sw.	62 20 N.	17 28 E.	−6·3	−5·1	
	Ratan, Sw.	64 00 N.	20 55 E.	−7·5	−5·6	
	Topilla, Fin.	65 02 N.	25 26 E.	−7·7	−3·5	
	Ykspihlaja, Fin.	63 50 N.	23 02 E.	−6·9		
	Vaasa, Fin.	63 07 N.	21 36 E.	−5·8		1 year's data incomplete.
	Rönnskär, Fin.	63 04 N.	20 48 E.	(−7·1	−3·8)	See note on Ventspils, Group 14.
	Mäntyluoto, Fin.	61 36 N.	21 29 E.		−3·8	1 year's data incomplete.
	Mean			−6·7	−3·6	
18	Skuru, Fin.	60 06 N.	23 33 E.	+2·6	+0·2	
	Helsinki, Fin.	60 09 N.	24 58 E.	+4·2	+0·7	
	Söderskär, Fin.	60 07 N.	25 25 E.	−2·7	+0·3	
	Viipuri, Fin.	60 42 N.	28 44 E.	−2·0	+3·2	
	Mean			+0·5	+1·1	
19	Oran, Alg.	35 43 N.	0 39 W.	+1·0		1 year's data missing.
20	Ajaccio, Corsica	41 55 N.	8 44 E.		−0·1	
	Bastia, Corsica	42 41 N.	9 26 E.		−6·8	14 years' data uncertain.
	Mean				−3·4	

Group No.	Station	Lat. ° ′	Long. ° ′	1901–10 to 1911–20 cm per decade	1911–20 to 1921–30 cm per decade	Remarks
21	Port Vendres, Fr.	42 31 N.	3 07 E.	+2·0	−0·2	
	Sète, Fr.	43 24 N.	3 42 E.	+2·0	−5·3	
	Port-de-Bouc, Fr.	43 24 N.	4 59 E.	+1·0	+0·9	
	Martigues, Fr.	43 24 N.	5 03 E.	+3·0	−5·2	
	Marseille (Pt. Vieux)	43 18 N.	5 21 E.	+3·5	+0·5	4 years' data uncertain.
	Marseille (Marégraphe)	43 18 N.	5 21 E.	+1·3	+0·7	
	La Ciotat, Fr.	43 10 N.	5 37 E.	+0·4	+0·6	4 years' data uncertain.
	Porto Maurizio, It.	43 52 N.	8 01 E.	+3·4		2 years' data incomplete.
	Mean			+2·1	−2·0	
22	Cagliari, Sic.	39 12 N.	9 10 E.	+2·2	+0·2	3 years' data incomplete.
	Bône, Alg.	36 54 N.	7 46 E.	+2·4	−1·1	5 years' data uncertain.
	Algers, Alg.	36 47 N.	3 04 E.		+4·2	
	Mean			+2·3	+3·3	
23	Civitavecchia, It.	42 03 N.	11 49 E.	+1·5		2 years' data incomplete.
	Napoli (Arsenale), It.	40 52 N.	14 16 E.	+3·8		10 years' data incomplete.
	Napoli (Mandraccio)	40 52 N.	14 16 E.	+3·4		7 years' data incomplete.
	Porto Corsini, It.	44 30 N.	12 17 E.	+6·2		1 year's data incomplete.
	Venezia, It.	45 25 N.	12 20 E.	+3·8		4 years' data incomplete.
	Mean			+3·7		
24	Sfax, Tunisia	34 44 N.	10 46 E.		+4·1	All data uncertain.
	Sousse, Tunisia	35 49 N.	10 37 E.		+4·0	All data uncertain.
	Mean				+4·0	
25	Catania, It.	37 30 N.	15 08 E.	+0·8		8 years' data incomplete.
	Palermo, It.	38 08 N.	13 20 E.	+1·2		6 years' data incomplete.
	La Goulette, Tunisia	36 49 N.	10 18 E.	−1·1	+1·2	
	Mean			+0·3	+1·2	
26	Aden, Arabia	12 47 N.	44 59 E.	−0·3		
27	Bombay (Prince's Dock), In.	18 57 N.	72 50 E.	+3·9		
28	Bombay (Apollo Bandar)	18 55 N.	72 50 E.	+1·9	−0·1	
29	Cocanada, In.	16 56 N.	82 15 E.	+0·5		
30	Port Blair, Andaman Islands	11 41 N.	92 46 E.	+2·0		
31	Kidderpore, India	22 32 N.	88 20 E.	−3·6		
32	Rangoon, Burma	18 46 N.	96 10 E.	+1·8		
33	Manila, P.I.	14 35 N.	120 58 E.	+1·2		1 year's data missing. 5 years' data incomplete.
34	Takao, Formosa	22 37 N.	120 16 E.		+3·2	
35	Hukabori, Japan	32 41 N.	129 49 E.	+0·7		
36	Hamada, Japan	34 55 N.	132 04 E.	+1·6		
37	Wazima, Japan	37 24 N.	136 54 E.	+2·5	+4·9	
38	Aburatubo, Japan	35 09 N.	139 37 E.	+6·0		
39	Hososima, Japan	32 25 N.	131 40 E.	−3·1	−0·9	
40	Kusimoto, Japan	33 28 N.	136 47 E.	+7·4		
41	Aikawa, Japan	38 18 N.	141 30 E.	+0·2		
42	Hanasaki, Japan	43 17 N.	145 35 E.	+3·1		
43	Otaru, Japan	43 13 N.	141 03 E.		+1·8	
44	Iwasaki, Japan	40 35 N.	139 55 E.	+3·7		

Group No.	Station	Lat. ° ′	Long. ° ′	1901–10 to 1911–20 cm per decade	1911–20 to 1921–30 cm per decade	Remarks
45	Sydney, Austral.	33 51 S.	151 14 E.	+1·8		
46	Honolulu, T.H.	21 18 N.	157 52 W.		+0·3	
47	San Francisco, U.S.	37 48 N.	122 28 W.	+1·5	−0·6	
48	Victoria, Can.	48 26 N.	123 23 W.		−0·3	
49	Seattle, U.S.	47 36 N.	122 20 W.	−0·3	−0·7	
50	Balbao, C.Z.	8 58 N.	79 34 W.		+1·4	
51*	Port Arthur, Can.	48 30 N.	89 00 W.	−4·5		Data for years 1907–39.
	Calumet Harbor, U.S.	47 10 N.	88 00 W.	−0·3		Data for years 1904–39.
	Michipicoten H., Can.	48 00 N.	84 50 W.	−4·1		Data for years 1915–39.
	Mackinaw City, U.S.	45 48 N.	84 40 W.	−2·0		Data for years 1900–39.
	Goderich, Can.	43 45 N.	81 45 W.	−1·0		Data for years 1910–39.
	Collingwood, Can.	44 31 N.	80 16 W.	−2·8		Data for years 1906–39.
	Cape Vincent, U.S.	44 07 N.	76 20 W.	−3·9		Data for years 1916–39.
	Mean			−2·7		

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REVISED NOMENCLATURE FOR DEPOSITIONAL COASTAL FEATURES

BY

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REVISED NOMENCLATURE FOR DEPOSITIONAL COASTAL FEATURES[1]

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ABSTRACT

An attempt is made to standardize the names of types of sand deposits along marine coasts, with special emphasis on geometry rather than on hypothetical origin. Distinct separations are made between submerged deposits which extend along the coast, here referred to as "bars," and emerged deposits, referred to as "barriers." A classification of cusp-shaped features is suggested. Most of the definitions are illustrated by air photographs.

Introduction.—There are few things more annoying to scientists than to be confronted with an article proposing an entirely new nomenclature. On the other hand, it is unfortunate to be yoked to an inadequate and confusing group of names conceived in a very early stage of investigation. The marine depositional features along the coasts represent such a case; they need more precise names and better definitions. This need is emphasized by examination of the great group of coastal air photographs which are available and has been recently impressed on the writer by a series of flights made along the northern coast of the Gulf of Mexico in connection with an American Petroleum Institute Project.[3] The definitions which follow are not particularly original; in fact, old names, slightly modified or restricted, are used where possible and new names are chosen largely for their simplicity and their descriptive significance. Johnson (1919) attempted to standardize terms for most of the features which are here discussed, but as Price (1951) and others have indicated, some of these names are inappropriate. Other features which are particularly impressive when seen from the air lack standardized names, although they may have local names not generally used in scientific articles and text books.

Barriers and bars.—One of the most confusing features of present terminology is the indiscriminate use of "bar." Originally this term as applied to the sea referred to slightly submerged sand ridges such as those existing at the entrances to harbors. Tennyson's immortal poem, "Crossing the Bar," no doubt helped establish this meaning for the term. However, on the plea that submerged bars may become elevated into beaches or islands, "offshore bar" has been used by Johnson (1919) and others to refer to sandy islands which extend for as much as

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[1] Contribution from the Scripps Institution of Oceanography, New Series No. 591. Manuscript received, June 26, 1952.

[2] Scripps Institution of Oceanography. The preceding attempt to standardize and expand terminology of coastal areas has been greatly assisted by W. Armstrong Price who offered many suggestions and after lengthy correspondence and some mutual adjustments has come to virtual agreement with the writer on definitions. Other suggestions were made by D. L. Inman and Ben B. Cox. The flights which produced much of the information and most of the photographs for the article were made through the courtesy of Gulf Oil Corporation, Stanolind Oil and Gas Company, and The Texas Company. Appreciation is expressed to Ben B. Cox, Lloyd E. Elkins, and Gerhard Herzog who kindly arranged the flights.

[3] A.P.I. Project 51, a study of sedimentation along the northern Gulf of Mexico.

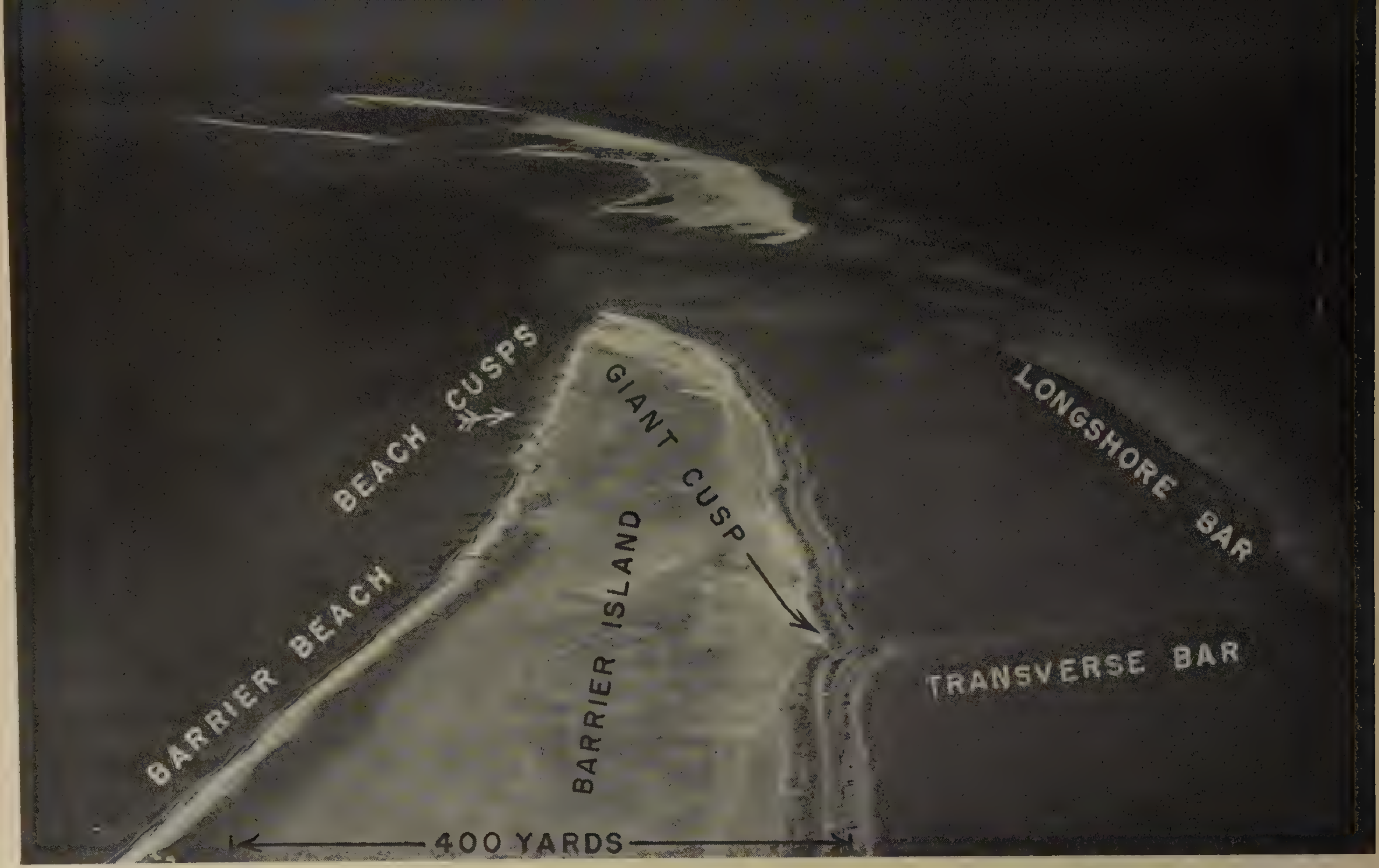
BEACH CUSPS
BARRIER BEACH
GIANT CUSP
BARRIER ISLAND
LONGSHORE BAR
TRANSVERSE BAR
400 YARDS

FIG. 1.—Two severed parts of Ship Island off coast of Mississippi, illustrating barrier beach on one side of barrier island. Two types of cusps and two types of bars can also be seen. Photograph by D. L. Inman.

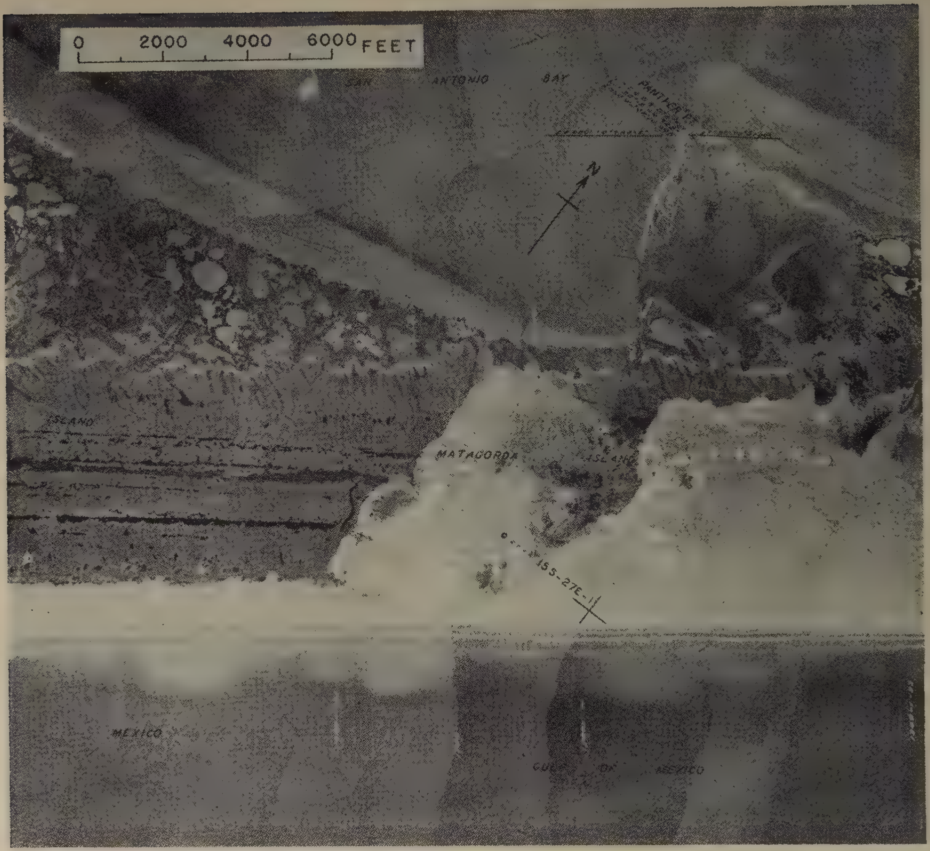

FIG. 2.—Large barrier island which crosses mouth of San Antonio Bay near Rockport, Texas. Dunes have migrated across parts of beach ridges. Swampy terrane with abundant lakes is typical of lagoonward side of barrier islands. Aerial mosaic by courtesy of Edgar Tobin Aerial Surveys.

a hundred miles along the coasts, attain widths of several miles, and have elevations up to a score or more of feet. To cross a bar of this sort requires more than a shallow-draft boat; in fact, one needs a highly maneuverable amphibious vehicle. Surely we should use different names for such widely different features. The word "barrier" as in "barrier beach" or "barrier island" offers a substitute and has already been used by several writers. Here, following Price (1951), the term "bar" is confined to sand shoals covered at least at high tide and "barrier" refers to the sand masses which extend along the coast and rise above high-tide level. Various types of bars and barriers are defined in following paragraphs.

Barrier beach.[4]—This term refers to a single elongate sand ridge rising slightly above the high-tide level and extending generally parallel with the coast, but separated from it by a lagoon (Fig. 1). The term should apply to islands and

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[4] Called an "offshore bar" by Johnson (1919), p. 259.

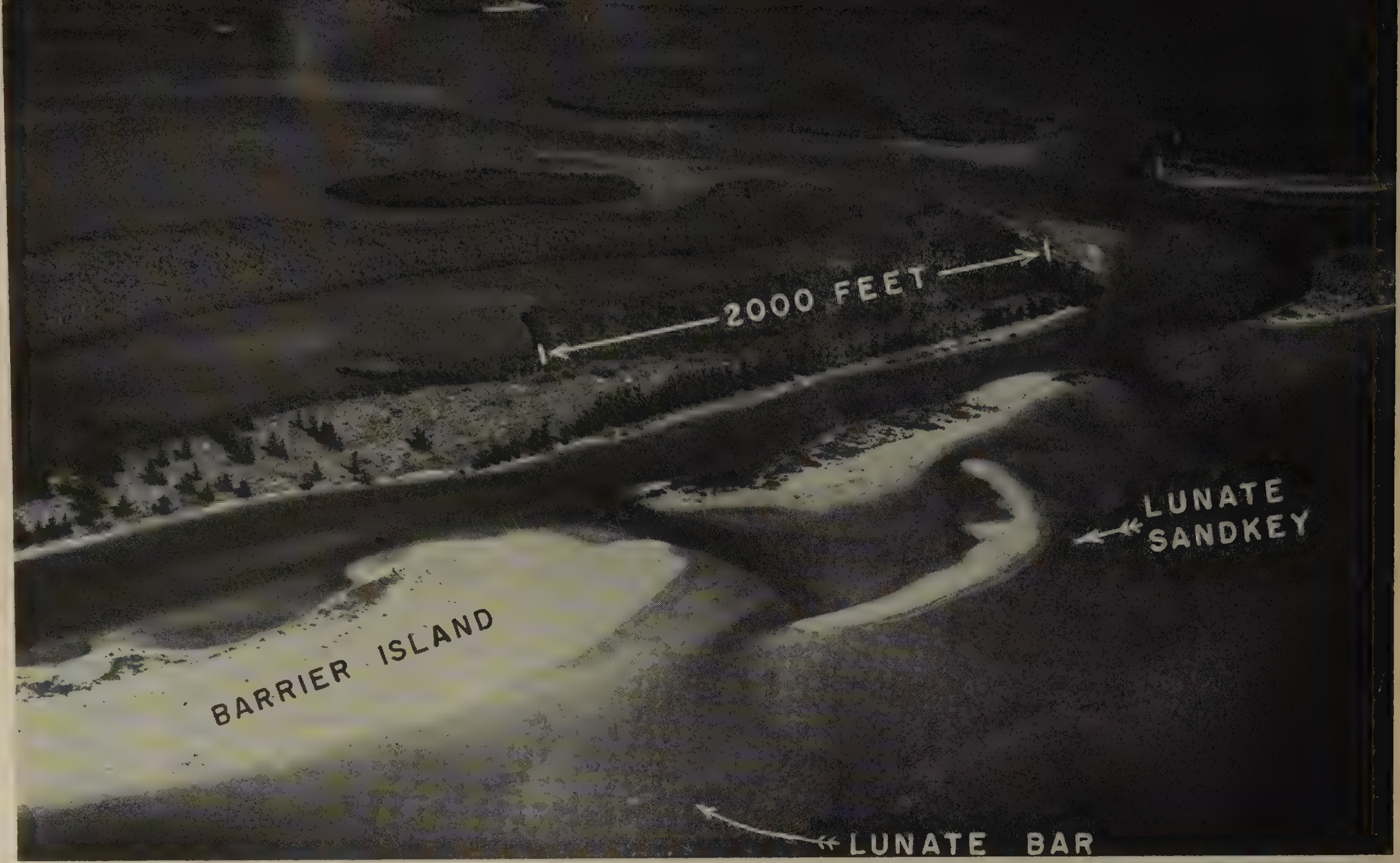
2000 FEET
LUNATE SANDKEY
BARRIER ISLAND
LUNATE BAR

FIG. 3.—Barrier islands, lunate sandkey, and lunate bar at Stump Pass along west coast of Florida near Fort Myers. Islands in background are old barriers beyond which new barriers have been built and the sandkey has formed since 1939. Various transverse bars are shown faintly through water. Photograph by D. L. Inman.

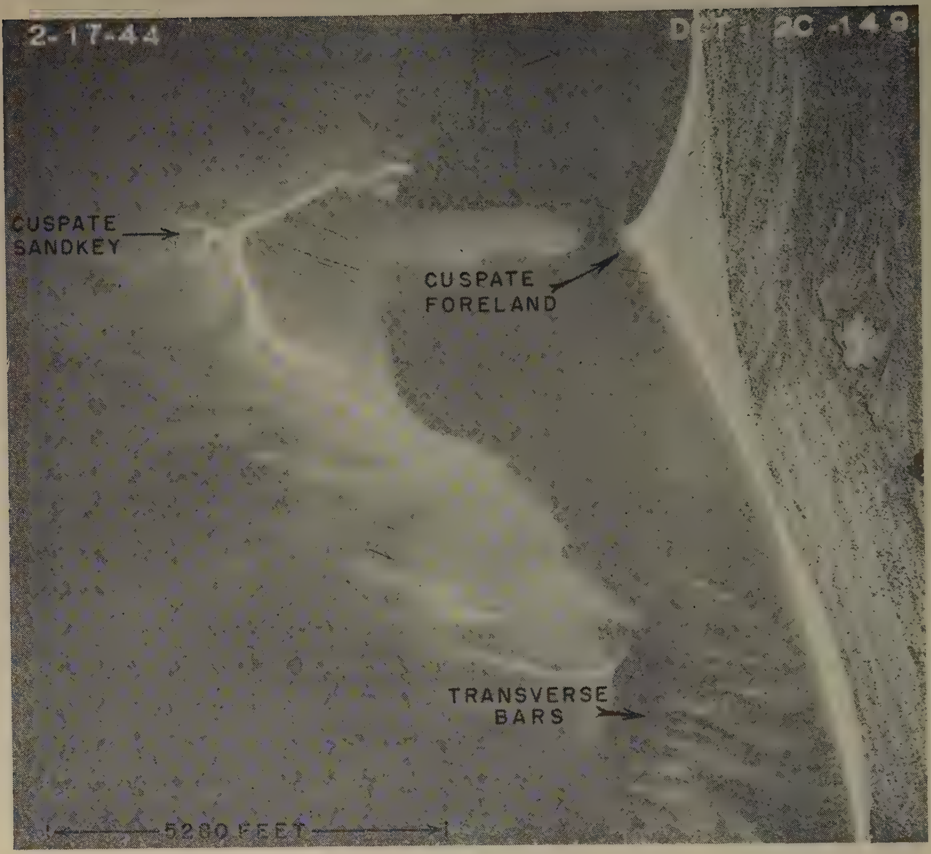

FIG. 4.—Newly developed cuspate sandkey outside small cuspate foreland on open coast near Fort Myers, western Florida. Note numerous transverse bars shown through the clear water and intricate pattern of beach ridges on shore. Vertical photograph by Coast and Geodetic Survey.

spits so far as they agree with the rest of the definition. The name has been used previously but was not restricted to single ridges.

Barrier island.[5]—This feature is similar to a barrier beach but consists of multiple instead of single ridges and commonly has dunes, vegetated zones, and swampy terranes extending lagoonward from the beach (Fig. 2). The inner ridges, as Price has indicated, may be eliminated by the encroachment of a series of dunes (Fig. 2). The D. W. Johnson terminology includes this complex feature in the catch-all "offshore bar." Comparison of Figures 1 and 2 indicates the desirability of employing different names.

Barrier spit.—Since many of the barriers are connected at one end to the mainland, "barrier spit" seems appropriate to add to the terminology although the difference between "barrier island" and "barrier spit" lies only in a connection

[5] Name suggested by Price (1951).

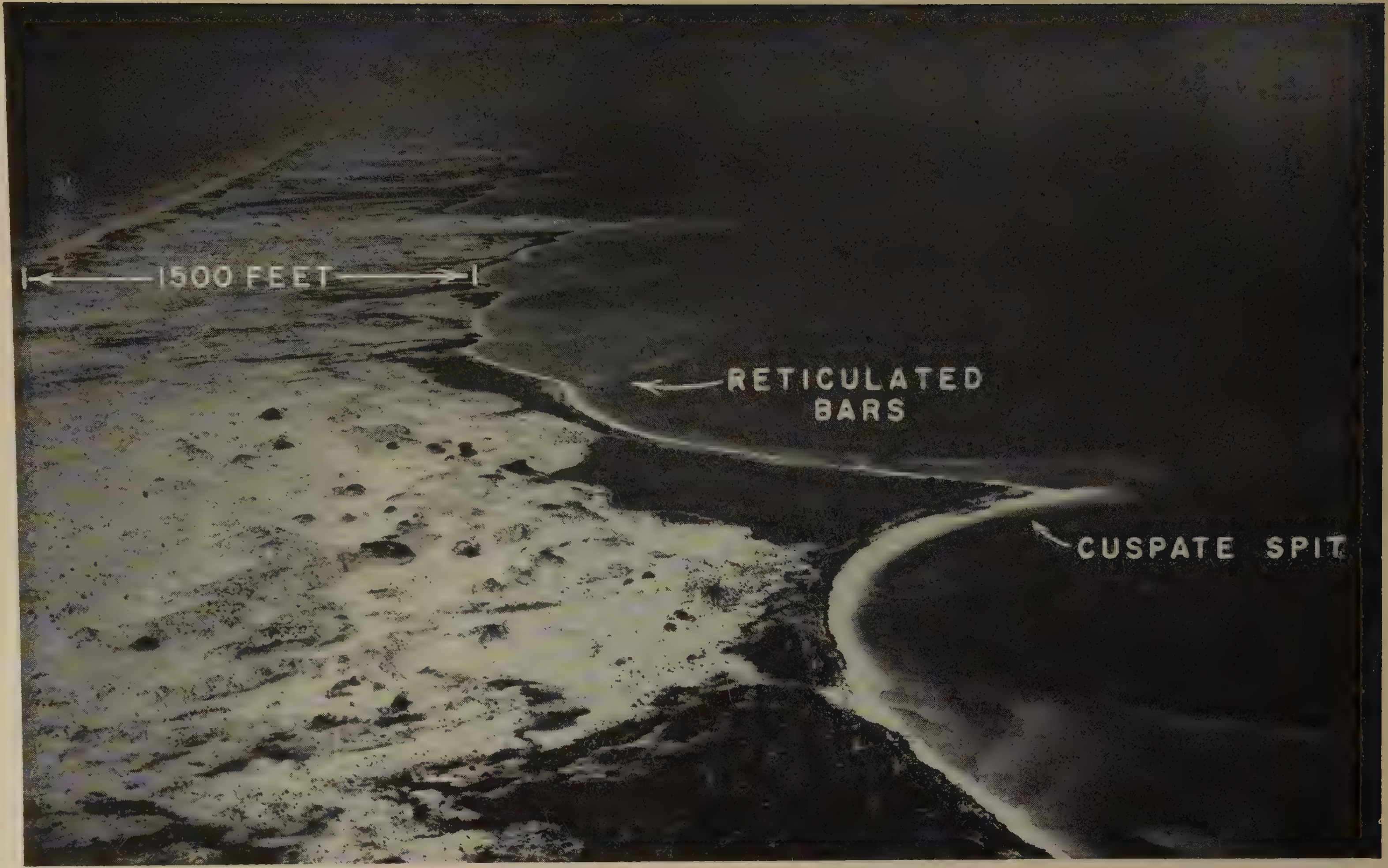
1500 FEET
RETICULATED BARS
CUSPATE SPIT

FIG. 5.—Cuspate spits built from barrier island into lagoon along northwest coast of Florida. Pattern of reticulated bars is shown between two spits. Photograph by D. L. Inman.

to the mainland which may be short-lived. Frequently hurricanes sever these connections by cutting new channels which, in turn, may be rapidly closed by longshore sand drift. In some places barrier islands become tied to the mainland by a delta which has built across the shallow intervening lagoon. It should be noted that the term "barrier spit" is not necessary where there is a single ridge since the term "barrier beach" is suggested for islands and spits alike. Obviously this combined term is not possible for barrier islands.

Bay barrier.—Where a spit has grown entirely across the mouth of a bay so that the bay is no longer connected to the main body of water the term "bay barrier" is proposed. This replaces "bay bar" a confusing term which fails to indicate whether or not the sand ridge is submerged or stands above the water level. Similarly "bay head bar" can be changed to "bay head barrier," avoiding the same confusion.

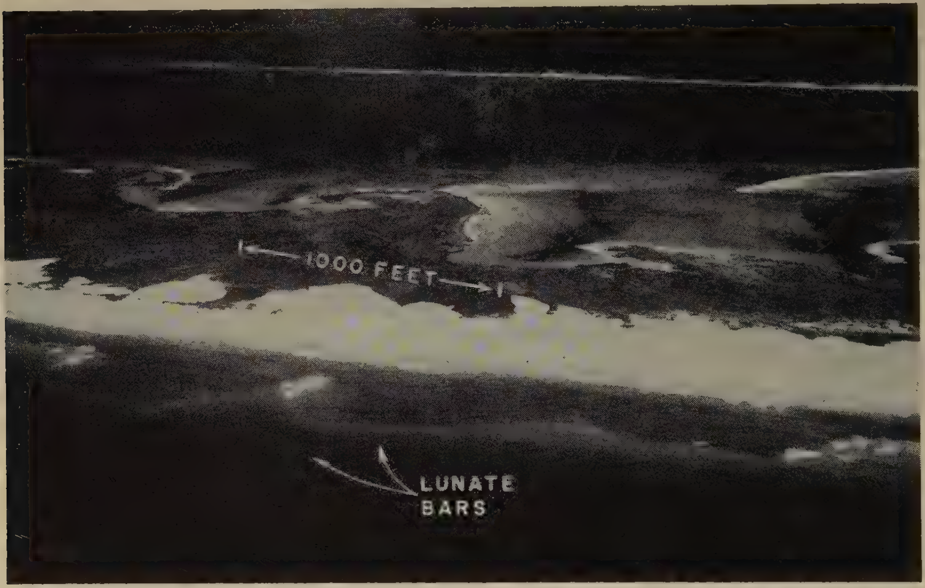

Fig. 6.—Lunate bars formed off barrier island near Panama City, northwest Florida. Photograph by D. L. Inman.

Barrier chain.[6]—This term can be used to include a series of barrier islands, barrier spits, and barrier beaches which extend along a considerable length of coast. The term is similar to "barrier" since the latter refers to all of the types previously defined, but "barrier chain" indicates continuity, thus providing the same contrast as between "mountain" and "mountain range."

Longshore bar.—This name refers to the sand ridges which extend generally parallel with the shoreline and are submerged at least by high tides. Longshore bars have been referred to in the past as "ball" as in "ball and low" (Johnson, 1919, p. 486). As discussed elsewhere (Shepard, 1950), the elongate character of these bars is not well indicated by "ball" which suggests a round object. Longshore bars (Figs. 1 and 2) are very common adjacent to straight beaches. They occur either as single ridges or as multiple ridges, the latter being common in areas with gentle seaward slopes. The bars can be seen from the air through the clear water, for example, along the Florida coasts (Fig. 4) and are indicated along other coasts by lines of breakers which recur in the same place with each wave (Fig. 2).

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[6] Suggested by W. Armstrong Price.

Transverse bars.—Less well known are the bars which extend at right angles to shorelines (Figs. 1, 3, and 4). The term "transverse bars" seems to be satisfactory for these features. They have been described elsewhere as "sand waves" (Gibson, 1951) and as "giant ripples" (Van Straaten, 1950), but these terms fail to indicate their important relationship to the shoreline. In a sense the longshore bars and transverse bars are akin to longitudinal and transverse sand dunes. On a smaller scale they are also similar to longitudinal and transverse ripple marks, the former related to oscillatory wave action and the latter controlled by longshore currents.

Reticulated bars.—A criss-cross pattern of bars, with both sets diagonal to the shoreline, is found in some areas (Fig. 5). As observed by the writer, these reticulated bars are found only in bays and in lagoons on the inside of barrier islands, but because of the intricate sounding pattern necessary to depict features of this sort their presence would be difficult to discover except where seen from the air through clear water. Therefore they may occur in other environments.

Sandkey or sand cay.—A small sand island which is not notably elongate parallel with the shore may be called a "sandkey" (Figs. 3 and 4). The word "key" is used for various types of islands along the Florida coast, including elevated coral reefs and barrier islands. The British use the word "cay" for the same thing and "sand cay" in British publications refers to the feature for which "sandkey" is used here.

Cuspate features.—There appear to be all gradations between the tiny cusps of protected shores which may be only a foot or less between cuspate points to huge cuspate capes like Canaveral and Hatteras. Along many straight open beaches there are cusps varying from about 30 to 200 feet between points, the distance increasing in general with wave height. Most of these, as indicated by Kuenen (1948), have depressions seaward from the cusps and elevations seaward from the troughs. Following common practice, these relatively small features are being referred to as "beach cusps."

Along other beaches slightly protruding cuspate points are more widely spaced, commonly 1,000-1,500 feet between points. These may be called "giant cusps." The distances separating these cusps do not vary according to wave heights so far as could be determined. The giant cusps have submarine ridges continuing seaward beyond them as transverse bars (Fig. 1). Along one or both

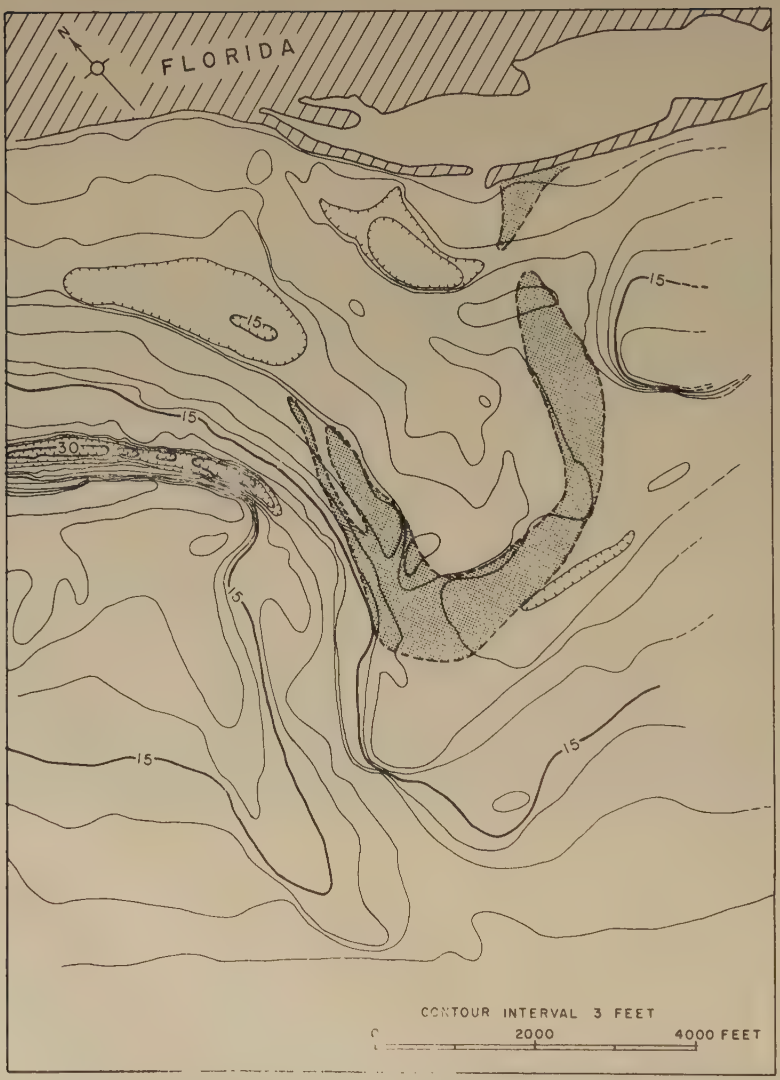
N
FLORIDA
15
15
30
15
15
15
15
CONTOUR INTERVAL 3 FEET
0
2000
4000 FEET

FIG. 7.—Newly developed lunate sandkey, shown by closely dotted area, superimposed upon contours from survey made in 1930. Location is at Tyndall Field, southeast of Panama City, Florida. Based on Coast and Geodetic Survey Hydrographic Sheet 5024.

ides of these bars there are deep channels. Ordinarily beach cusps are poorly leveloped between giant cusps. Possibly the beach cusps are missing because of trong current action observed in the giant cusp areas. The currents turn seavard along the giant cusps and thus account for the adjacent channels.

Next in the cusp size scale are the prominant points or horns found extending nto the bays and lagoons inside many barriers (Fig. 5). These may be referred o as "cuspate spits." Like giant cusps, they have shoals extending out from the usp point although these shoals occur independently as shown in Figure 5. The uspate spits have much more prominent points than giant cusps and distances etween points are ordinarily a mile or more. These spits are more common on he barrier side of the lagoon, but are found also on the mainland side and in some places two points are found *vis-à-vis* with or without a connecting shoal.

The largest of the cusps occur along the open coasts as capes, measuring in some places miles across their apices and extending for miles seaward from the rest of the coast. These capes have been called "cuspate forelands" (Johnson, 1919, p. 324) and this name seems appropriate for such features as Cape Hatteras, Cape Fear, and Cape Canaveral. The cuspate forelands contain a series of ridges with troughs which may be above water as in Cape Canaveral or submerged as at Cape Hatteras. A relatively small cuspate foreland is shown in Figure 4.

In attempting to divide the cusps, it was realized that gradational cases are found just as there are all gradations between ponds and lakes or brooks and rivers, but in general the differences observed along the coasts of the United States appear to allow an easy classification into the cusp types listed.

Cuspate bars and sandkeys.—Where the cusp form is submerged, but may either be seen from the air through the clear water or is known through soundings or surf patterns, the feature may be called a "cuspate bar." These bars may be built up above the surface to form islands which should then be called "cuspate sandkeys." Several transformations of this type have occurred along the west Florida coast in recent years (Figs. 4 and 7).

Lunate bars and sandkeys.—The lunate or crescent shape of bars and small islands is perhaps more common than the cuspate form. Such "lunate bars" and "lunate sandkeys" are found commonly off passes between barrier islands or off the entrances to harbors. Where the waves are large the lunate bar may have a deep crest, for example, "Fivefathom Shoal" outside the Golden Gate at San Francisco. Where the waves are small, the bar is likely to be very shoal or even stand above the surface (Fig. 3). At both ends of the bar or sandkey there is ordinarily a channel maintained by the tidal currents. Elsewhere the channel may cut through the center of the bar or island.

Another type of lunate bar is found outside some beaches of seas with small tidal range such as the Mediterranean and the Gulf of Mexico. Most of these bars occur off straight beaches (Fig. 6) so that they are not related to beach cusps. The lunate bars appear to be a modification of longshore bars since they may be traced laterally into ordinary longshore bars and since they are not directly connected to the beach. So far as is known, this type of lunate bar does not build above the surface.

Concluding remarks.—No attempt has been made here to present an exhaustive coverage of the features of coastal deposition. It is hoped that other writers will propose names to fill some of the gaps which have been left. It is recommended that such attempts avoid complicated names which are difficult to establish in the literature.

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years (Gutenberg, 1941). Material slightly denser than 3 g cm^{-3} will flow within the earth's mantle from regions beneath the oceans to regions beneath continents from which ice has been removed. The flow will be accompanied by a decrease in the length of day, and a reverse movement of the pole of rotation. The sea bottom, and with it the sea surface, will eventually drop by about one third the amount of the initial rise in sea level. For a drop in sea level by z cm during this interval, the numerical values are roughly three times those in table 1, and of opposite sign.

In this discussion, the term "rapid" has referred to a time interval short compared to the "relaxation time" T. If a rise is sustained over an interval as long as or longer than T, the addition of water mass and the removal of mantle material occur concurrently. This is equivalent to an addition of mass at the sea surface, and a corresponding removal beneath the sea bottom. Under these circumstances, the numerical values of τ/z, λ/z, μ/z are greatly reduced compared to those in table 1. The reduction factor is of the order of a/h, where a is the radius of the earth, and h the depth of isostatic adjustment. For h equal to 300 km, a/h equals 20.

The sea level will also rise if the oceans become warmer, even if no ice is melted. An increase in the temperature of all the ocean water by 1°C would raise the sea level by 60 cm! Again this is equivalent to an addition of mass at the surface and a corresponding removal at depth. Numerical values are reduced by a factor of the order of a/h′ compared to those in table 1, where h′ is the depth to which the water is heated. The reduction factor is certainly larger than 1000.

The foregoing relationships are useful in interpreting observations during historic times of changes in sea level and in the earth's rotation. For example, about 3000 years ago, during the postglacial temperature maximum, sea level is believed by Daly (1920, 1927) and others (Kuenen, 1950, pp. 448, 537-539) to have stood approximately five meters higher than it does today. A drop by 5 m. would result in a decrease of the length of day by the following amounts, depending on the condition of lowering:

(1)	rapid growth of ice caps	30.	milliseconds
(2)	isostatic afterflow following rapid melting of ice caps	90	”
(3)	slow freezing of ice caps	∽1.5	”
(4)	cooling of entire oceans by 8°C.	∽0.03	”

From an analysis of ancient observations by Greek, Babylonian, Chinese and Egyptian astronomers, Fotheringham (Jeffreys, 1929, p. 255) found that the day has lengthened by 2.0 milliseconds per century in historic times. Subsequently there has been a "secular decrease" in the values given in the literature for the secular increase of the length of day. The most recent investigation by Brouwer (1952), based largely on the comprehensive work by Spencer Jones, gives a secular increase by 1.35 ± 0.55 milliseconds per century during the last 3000 years. A modification by Urey (1952, pp. 80-87) of Jeffreys's theory concerning the effect of tidal friction leads to the result that the observed secular accelerations of sun and moon can be made consistent only if it is assumed that tidal friction accounts for 1.7 times the observed lengthening of the day, and that changes in the earth's moment of inertia make up the difference. The required dissipation of the earth's rotational energy by tidal currents lies within the range of values estimated by Jeffreys. We have, therefore, from astronomic evidence the following changes in the length of day:

due to tidal friction	+2.3 ± 1.6	milliseconds/century
due to moment of inertia	−0.9 ± 0.6	"
total change	+1.4 ± 0.4	"

The values and probable errors follow from Brouwer (1952).[1]

We are concerned here only with the part due to changes in the earth's moment of inertia, i.e., a shortening of the day by 27 ± 18 milliseconds in 3000 years. The probable error is very large; still, some useful information can be gained from a comparison with our calculated values corresponding to changes in sea level under various conditions. The value 27 ± 18 milliseconds is consistent with a rapid growth of ice caps (condition 1), but not with Daly's suggestion of isostatic afterflow following a rapid retreat of ice caps at the close of the glacial period (condition 2). Combinations of conditions

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[1] After this note had been in press, Professor Mintz called our attention to an additional effect, first noted by Kelvin (Royal Soc. Edinburgh Proc., 1882, vol. 11, p. 396), which is not included in Brouwer's calculations. It is known from barometric observations that the semi-diurnal component in atmospheric pressure reaches a maximum before noon. The result is an accelerating torque by the sun on the atmosphere. The present estimate of this torque is 3.6 ± 0.2 x 10 dynes cm. The resulting decrease in the length of day by 0.17 milliseconds per century would modify the amount ascribed to the moment of inertia from -0.9 to -0.7 milliseconds per century. In the further discussion we have used Brouwer's value of -0.9 milliseconds per century.

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Dredging Life from the Bottom of the Sea

by

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DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

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OFFICE OF NAVAL RESEARCH
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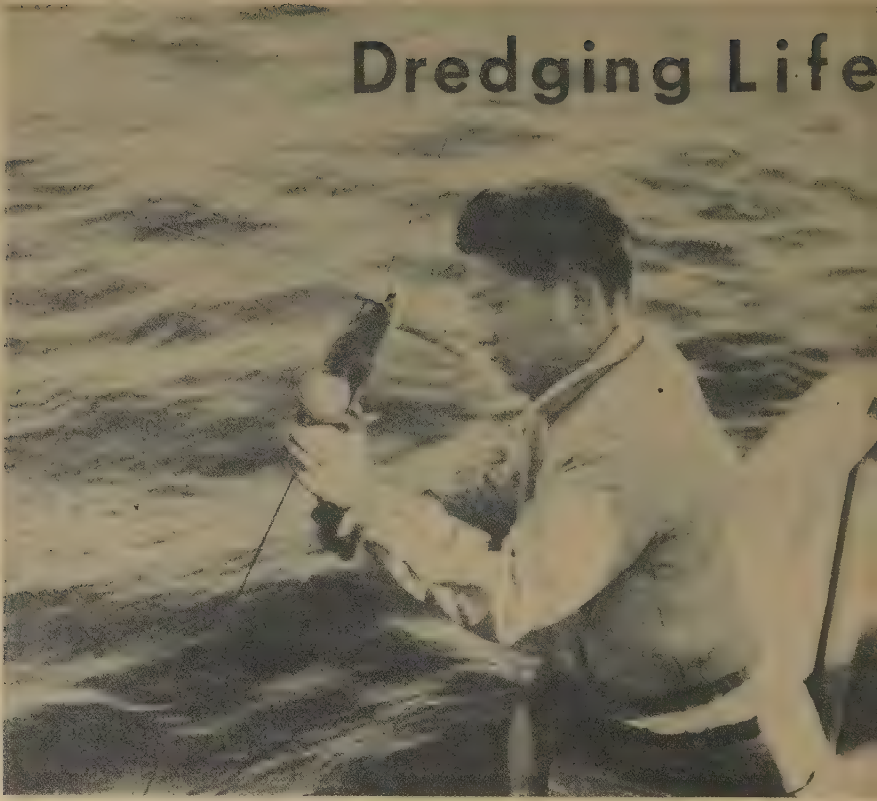
Dredging Life



Fishing in the deepest parts of the sea calls for very special equipment. Some — like the bathysphere shown far right (opposite) — was already available. Other devices, however, had to be invented — for example, the bacteriological water sampler which Richard Y. Morita (above) is shown removing from the hydrographic wire. This device was developed by the author to be sterilized and sent to any depth to collect samples of uncontaminated water. Several can be operated in tandem by means of messengers — i. e., weights that slide down the wire to activate the opening mechanism at the desired depth. Other instruments used are shown on p. 16.

Bathysphere aboard *Galathea*.

the Bottom of the Sea

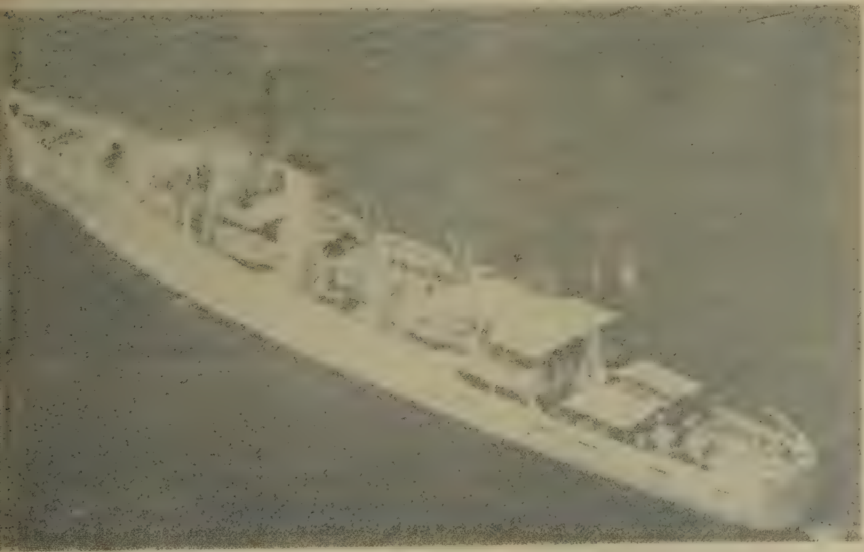
by

Claude E. ZoBell
Scripps Institution of Oceanography

Dr. ZoBell lashes a piece of high-pressure apparatus to the cable before it is lowered.

Until recently the dark crevices of the ocean's lowest depths were assumed to be without living organisms of any kind, the possibility of such life supposedly being precluded by high hydrostatic pressure, low temperature, lack of food, and other adverse conditions. Few observations, however, had been made at depths exceeding about a mile and a fourth, although roughly half of the vast sea floor is under 2-1/2 miles or more of water. It was therefore an event of unusual scientific interest when the Galathea Deep Sea Expedition recently demonstrated for the first time that organisms occur in the lowest depths of the sea.

The Galathea is a 1630-ton Danish frigate converted for exploring the deep sea. During its 60,000-mile cruise around the world

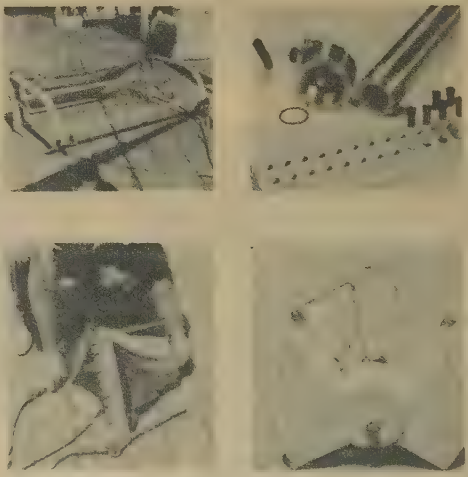


The expedition's ship, R. D. N. Galathea in 1950-52, this 258-foot ship was manned by some 90 officers and men of the Royal Danish Navy, with about 15 scientists as supercargo On separate phases of the expedition the Office of Naval Research was represented by Dr. Rolf L. Bolin, an ichthyologist from Stanford University, and Mr. Richard Y. Morita and Dr. Claude E. ZoBell, both microbiologists from the Scripps Institution of Oceanography.

The ship was equipped with the best navigational aids, sounding devices, hydrographic apparatus, and gear for collecting oceanographic data. The step-tapered dredging cable was almost 8 miles long, its diameter ranging from nearly half an inch for the first 2 1/4 miles to about an inch for the final 5/8 of a mile. With a breaking strength of nearly 40 tons, this unique braided-wire cable, which weighed 8.7 tons when submerged in water, could have safely lifted a load of 10 tons from the deepest known depression in the sea.

Bottom samples were collected with an assortment of sledge trawls, grabs, and mud-corers. A sledge trawl consists essentially of a sturdy, rectangular, metal frame to which a baglike net or metal mesh web is attached to retain the catch. Since the trawl is towed along the sea floor at about one knot, it can be expected to catch only stationary or slowly moving creatures. For different kinds of bottoms the Galathea employed trawls having beams with a width of mouth opening of 3, 6, 10, and 20 feet respectively.

The grab consists of a pair of heavy, metal, hinged jaws held open during descent. Upon contacting the bottom a trigger-like mechanism



These instruments enabled scientists to fish up strange creatures from the bottom of the sea. At left is a three-foot beam dredge; above are the six-foot sledge trawl for catching marine organisms, and the pressure vessel in which they have to be stored; below are a bottom trawl and the Peterson grab.

Two sections of bottom corer being rigged on the Horizon (a Scripps Institution Ship). The top section of the corer rests on the deck near the feet of the author, left.

releases the jaws, permitting them to bite off as much as a cubic yard of soft bottom material.

A bottom-corer is a long piece of steel pipe with a sharpened nose. Held in a vertical position with the nose pointing down, it is lowered rapidly to the sea floor, where its own weight may drive it a meter or more into the mud. Ingenious devices have been developed by which streamlined lead weights, multiple explosive charges, or hydrostatic pressure barrels provide for greater penetration. The mud core is held in the pipe by automatic one-way valves or core catchers. Ordinarily the core barrel is lined with a thin transparent plastic sleeve or cylinder to facilitate the removal of the mud core intact.

On 15 July 1951 a mud core was recovered from the Philippine Trench east of Mindanao Island at a depth of six and one-half miles. Examination with a phase-contrast microscope showed it contained large numbers of active microorganisms. An hour or two after recovery of the sample all evidence of life had disappeared from the portion kept at normal temperature and pressure, presumably because the organisms were unable to survive the sudden change in climate attending their transfer from the deep sea floor. This was not surprising, considering that the temperature at the bottom is near 3°C and the hydrostatic pressure is about 1,040 atmospheres, compared with a surface water and air temperature of 30°C and a pressure of one atmosphere.

It was not impossible, however, to keep some of the denizens of the deep alive. Shortly after being brought to the surface, portions of the sample from the sea floor were transferred aseptically to refrigerated stainless-steel vessels in which the specimens were subjected to the pressure of the ocean bottom. Under these conditions the microorganisms not only remained alive but specimens planted in appropriate nutrient media reproduced and exhibited evidence of biochemical activities. By the use of a method familiar to microbiologists (the minimum dilution method) we demonstrated that the deep sea sediment from the mud-water interface contained from thousands to millions of living bacteria per gram. Probably many more failed to reproduce in the nutrient medium or perished in transit from the sea floor to the refrigerated pressure vessels.

These observations on the occurrence of living bacteria were duplicated on other samples from the Philippine Trench. Barophilic bacteria, whose well-being requires high pressure, were also found in abundance in bottom deposits collected from the Soenda Deep off the southwest coast of Java, the Weber Deep in the Banda Sea, the Solomon Deep near the Solomon Islands, and from the Kermadec-Tonga Trough north of New Zealand, at depths ranging from four and one-half to six miles.

Barophilic bacteria from the deep sea differ in many respects from organisms found in soil, sewage, or shallow marine bottoms. Learning how their protoplasm, enzymes, and physiology differ from surface-dwelling organisms, which are ordinarily damaged by high

Some of the Danish scientists aboard worked twelve hours a day examining deep-sea specimens.

Dr. ZoBell, back in his dry-land lab, investigates the behavior of enzymes at different hydrostatic pressures.

pressure, may contribute to our understanding of the fundamental processes of life. In any case knowledge of the barophilic organisms is essential to an understanding of life at great sea depths.

Besides bacteria, representatives of 25 different families of animals from depths exceeding four and one-half miles were identified by the Danish zoologists on the Galathea Expedition. The bottom fauna from depths exceeding six miles included many animals belonging to the same biological classifications as anemones, water polyps, clams, sand fleas and lobsters (i.e., 27 varieties of actinians, more than a hundred holothurians, five kinds of bivalves, three amphipods, five worms, and two crustaceans). Although the animals were dead and distorted when they reached the surface, their normal habitat unquestionably is the deep sea floor where pressures of the order of 1,000 atmospheres prevail.

One may wonder about the source of food for animals living far below the zone of green vegetation. Discovery of fragments of cellulose and lignin from surface-dwelling organisms shows that a small quantity of organic matter from the higher regions reaches the deep sea floor. This meagre supply may be supplemented by bacteria, which are known to serve as a source of food for many marine creatures. This idea gains credence from the fact that most of the animals found on the deep sea floor were types adapted to feed on small particles. The gut of some, in fact, was gorged with microorganisms.

The next question which naturally arises is: How do deep sea bacteria obtain their food and energy? They get it primarily from dissolved and colloidal organic matter which is continually supplied by the movement of water masses in most ocean basins. Bacteria also assimilate organic wastes, including animal excreta, converting an average of from 30 to 40 per cent of its carbon content into nutritious cell substance. Autotrophic bacteria that fix carbon dioxide while oxidizing ammonia, nitrite, elementary hydrogen, or other inorganic substances as a source of energy may also contribute to the food cycles in the deep sea.

Although the Galathea Expedition and related research has established the existence of life at great oceanic depths, the "biggest fish" probably got away. Any large agile animals that might live on the deep sea floor could escape our rather cumbersome collecting devices which had to be manipulated through miles of water from a ship on a storm-tossed sea. Even the barophilic bacteria that were captured alive probably represent the hardiest varieties rather than those typical of the abyss, for the others probably expired in transit. Only by perfected procedures and extensive effort will we learn more about the mysteries of life in the last great unexplored frontier that encompasses approximately one-third of the earth's surface.

* * *

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THE MEMBRANE FILTER IN MARINE MICROBIOLOGY[1]

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The advent of the membrane filter has opened a new path for the study of bacteria. The apparatus and procedures have been described by Clark *et al.* (1951) and Goetz and Tsuneishi (1951).

The membrane filter used in these experiments employs a filter membrane consisting of a mixture of cellulose esters which can be carefully controlled to provide different effective pore sizes (Goetz, 1951). The effective pore size used in the following experiments is referred to as "Z" value which describes the specific flow resistance. Z is determined by the time required for one ml of distilled water to pass through one cm of filter area at a pressure of 70 cm of Hg. A filter of Z = 0.8 to 1.0 seconds has an effective pore size of approximately 0.4 microns. The filter type Z = 1.5 to 2.0 seconds (table 1) was able to retain marine bacteria while a filter type Z = 0.8 to 1.0 seconds capable of complete retention of fresh water-born microorganisms proved to allow certain marine bacteria to pass. The filter membranes were sterilized with ethylene oxide vapor for four hours in a closed system. The abundance and kinds of bacteria retained by the filter may be determined either by cultural procedures or by their direct microscopic observation. The latter can best be accomplished with a phase contrast microscope after rendering the filter membrane transparent with an inert, neutral oil having a refractive index of 1.49.

With the use of appropriate nutrient media and conditions of incubation, either aerobes or anaerobes can be cultivated on the surface of the filter membranes. The nutrient sea water media for the membrane filter technique were concentrated by using from two to four times the normal solid ingredients per volume of water. After quantitatively removing the bacteria from a water sample by its passage through a filter membrane, the effluent side of the latter was placed on a sterile absorbent pad soaked with suitable nutrient medium. The bacteria on the surface of the membrane obtain the soluble nutrients from the pad below by capillary attraction and diffusion. After a few hours' incubation in a moist chamber at 25 C, microcolonies resulting from multiplying bacteria can be counted with a low power dissecting microscope. The colonies appear more rapidly on the filter membrane than on standard agar or gelatin plates. If enumeration must be delayed, the colonies on the membranes may be preserved by formaldehyde vapors and kept for counting later.

For the experiments on aerobic bacteria, nutrient sea water medium as described by ZoBell (1946) was used in concentrated form. The oxidation-reduction indicator, 2,3,5-triphenyl-tetrazolium chloride as used by Goetz and Tsu-

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[1] Contribution from the Scripps Institution of Oceanography, New Series no. 594.

TABLE 1

The filtering efficiency of the Z = 0.8 to 1.0 and Z = 1.5 to 2.0 second filter membranes for marine bacteria naturally present in sea water as determined by bacterial counts with nutrient sea water medium

FILTER MEMBRANE	SAMPLE NO.	VIABLE CELLS/ML IN SEA WATER	VIABLE CELLS/ML IN FILTRATE
Z = 0.8 to 1.0	1	3,700	5
	2	10,000	0
	3	4,500	4
	4	4,300	4
	5	10,000	12
	6	8,500	4
Z = 1.5 to 2.0	1	1,150	0
	2	950	0
	3	914	0
	4	991	0

TABLE 2

The effect of 2,3,5-triphenyl-tetrazolium chloride (TPTZ) as an oxidation-reduction indicator on the growth of marine bacteria as expressed by viable cell counts with the MF and plating methods

SAMPLE NO.	TPTZ PRESENT MF METHOD CELLS/ML	TPTZ ABSENT PLATING METHOD CELLS/ML
1	1	230
2	2	280
3	140	670
4	100	914
5	112	991
6	180	950

TABLE 3

The minimum number of viable bacteria in different sea water samples when incubated at 25 C as determined by the MF method and the standard plating or dilution methods

MEDIA	SAMPLE NO.	MF METHOD	PLATE OR DILUTION METHOD
Sea water broth (aerobic)	1	7,800	5,500
	2	2,700	1,430
	3	3,400	970
	4	110	130
	5	16	2
	6	2	2
	7	3	2
SO_4-reducing (anaerobic)	1	150	62
	2	370	0

neishi (1951), was incorporated in the sea water medium in earlier experiments. As table 2 indicates, 2,3,5-triphenyl-tetrazolium chloride inhibited approximately 90 per cent of the marine bacteria which would normally grow in its absence. When 2,3,5-triphenyl-tetrazolium chloride was omitted in later experiments (table 3), it was found that approximately 30 per cent more bacterial colonies per unit of water developed on membranes treated with nutrients than on agar plates containing comparable nutrients. The higher colony counts obtained on the membranes are believed to be due in part to the fact that some marine bacteria are injured by exposure to the plating temperatures of agar (ZoBell and Conn, 1940).

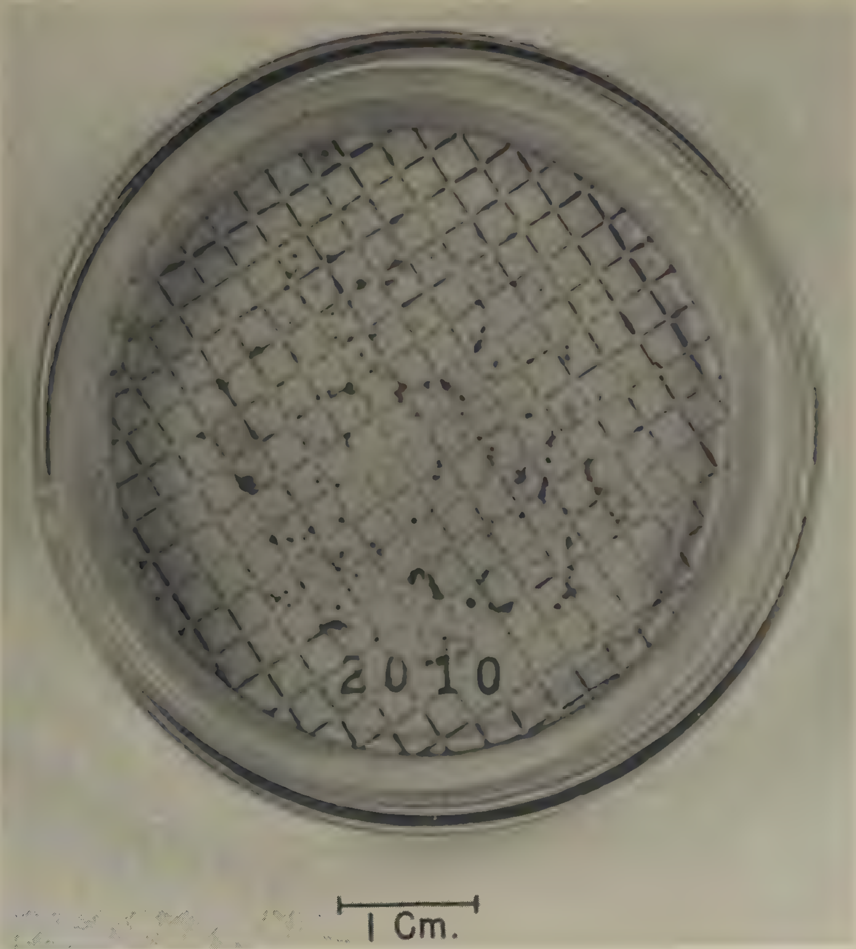

Figure 1. Photograph of a membrane filter showing the presence of small black colonies of sulfate reducing bacteria as filtered from 10 ml of raw sea water after 7 days' incubation at 25 C under anaerobic conditions.

Anaerobes may be cultivated on the bacteria-laden membranes when the latter are placed on pads soaked with appropriate nutrient medium as described by Sisler and ZoBell (1950). After the membranes were incubated for seven days in a moist chamber at 25 C from which oxygen was excluded, preferably by the chromium-sulfuric acid method, even fastidious sulfate reducing bacteria developed colonies. These could be distinguished from colonies of other anaerobes by the black zone formed by the reaction of hydrogen sulfide with iron in the medium (figure 1). The cloudy black zone which is associated with the growth of sulfate-reducers in agar media and which tends to mask the original colony site was absent. Therefore the colonies on the filter membrane were easily detected. In these experiments (table 3), from two to three times as many marine sulfate reducers were detected as could be discerned by the minimum dilution method. The colonies of sulfate reducers appeared under the microscope to be small and raised, having a metallic sheen with concentric black rings. This method may prove to be valuable for obtaining pure cultures of the sulfate reducing bacteria, whereby single colonies may be picked from the surface of the membrane.

ACKNOWLEDGMENT

Acknowledgment is accorded to Dr. A. Goetz, California Institute of Technology, Pasadena, California, who graciously supplied the filter membranes used in these experiments and to Dr. C. E. ZoBell of Scripps Institution for suggestions and criticisms during this investigation.

SUMMARY

This new technique affords some manifest advantages. It is an excellent tool for sampling marine psychrophilic bacteria which constitute a major portion of the bacteria in the sea. The results would indicate that higher numbers of bacteria capable of multiplying on sea water broth may be present in sea water than may be determined by standard methods. In addition, the small amount of necessary equipment, the exclusion of solidifying agents, and ease of manipulation make the equipment highly desirable for use at sea.

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Transactions, American Geophysical Union Volume 33, Number 6 December 1952

THE DIRECT CONSTRUCTION OF WAVE RAYS

R. S. Arthur, W. H. Munk, and J. D. Isaacs

(Contribution from the Scripps Institution of Oceánography, New Series, No. 595)

Abstract--In the construction of refraction diagrams for ocean waves the rays (orthogonals) can be drawn more accurately if the approximate formula $\Delta\alpha = (\Delta L/L_{ave}) \tan \alpha$, used by JOHNSON, O'BRIEN, and ISAACS [1948] in the preparation of refraction protractors, is replaced by $\Delta\alpha = \sin^{-1} [(1 + \Delta L/L) \sin \alpha] - \alpha$. In these formulas, α is the angle between wave crest and depth contour and L the wave length taken at the beginning of any contour interval; $\Delta\alpha$ and ΔL are the corresponding changes over the contour interval. A modified procedure for the construction of rays is presented.

Introduction--JOHNSON, O'BRIEN, and ISAACS [1948; henceforth referred to as JOI] have greatly improved the construction of refraction diagrams by devising a method for the direct construction of wave rays (orthogonals), which eliminates the need for first drawing the wave crests. The JOI method is based on an approximate formula, derived from refraction geometry, for the change in direction of a ray between adjacent contours. In the present paper the same problem is considered using as a starting point the differential equations of the ray path. The results lead to modifications which simplify and improve the accuracy of the JOI method.

First, a proposed procedure is developed without reference to JOI; then the two methods are compared. The accuracy of refraction diagrams can be improved either by following the JOI method but re-computing the protractors on the basis of the new equation (without added difficulties in their use), or by following the method proposed here.

The equation of the ray--Let x = x (s) and y = y (s) denote the coordinates of a point on a wave ray in terms of the distance s measured along the ray from some arbitrary point. Then if $\theta = \theta(s)$ denotes the angle between the tangent to the ray and the x-axis (Fig. 1), the differential equations of the ray are

$$\frac{Dx}{Ds} = \cos\theta \qquad \frac{Dy}{Ds} = \sin\theta \quad . . \text{(1a,b)}$$

$$\frac{D\theta}{Ds} = -\frac{1}{c}\frac{Dc}{Dn} \quad . . . . \text{(1c)}$$

where c = c (x,y) is an arbitrary, but known, two-dimensional field of wave velocity. The operators D/Ds and D/Dn refer to differentiation in the direction of the tangent and normal to the ray, respectively, and are defined by

$$\left.\begin{aligned} \frac{D}{Ds} &= (\cos\theta)\frac{\partial}{\partial x} + (\sin\theta)\frac{\partial}{\partial y} \\ \frac{D}{Dn} &= -(\sin\theta)\frac{\partial}{\partial x} + (\cos\theta)\frac{\partial}{\partial y} \end{aligned}\right\} \text{(2a,b)}$$

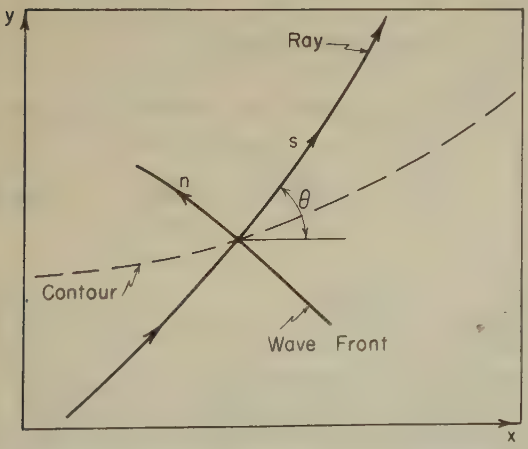


Fig. 1--Definition diagram for ray equation

Identical or equivalent forms of (1a,b,c) are derived in physics texts on light and sound [for example, FRANK, BERGMANN, and YASPAN, 1946]. Equations (1a,b) simply state that the ray makes an angle θ with the x-axis. Equation (1c) states that the curvature of the ray, Dθ/Ds, depends on Dc/Dn, the gradient of wave velocity in the direction of the normal. Equation (1c) is a consequence of Fermat's principle, according to which the ray is a path of minimum travel time. The derivation of (1c) requires that c, ∂c/∂x, and ∂c/∂y be continuous. It is assumed that this condition holds in practice since we know c only through measurements of water depths at specified positions and interpolation therefrom.

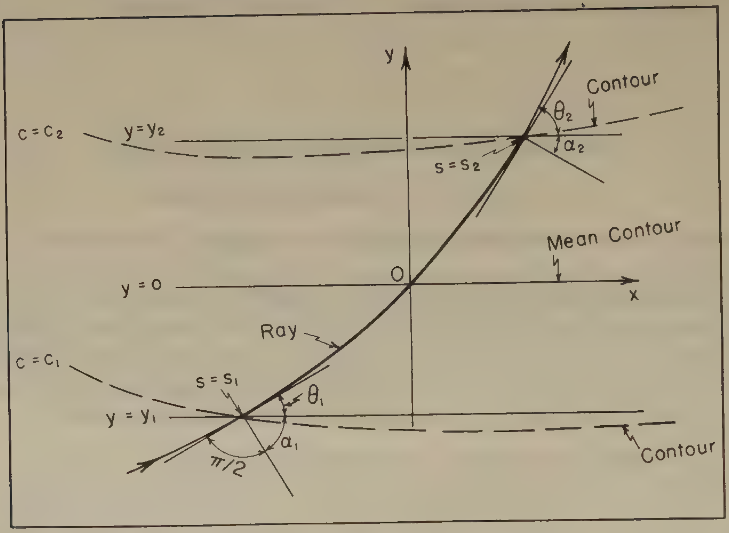


Fig. 2--Definition diagram for ray crossing contour interval

Integration between contours--The equation

$$\frac{D\theta}{Ds} = \frac{1}{c}\left[(\sin\theta)\frac{\partial c}{\partial x} - (\cos\theta)\frac{\partial c}{\partial y}\right]$$

is to be integrated between two adjacent bottom contours which are labeled in terms of the respective wave velocities c_1 and c_2 (Fig. 2). Since c (x,y) is not known analytically, approximate methods must be used. If the x-axis is taken in the direction of the mean contour, as shown in Figure 2, then by Taylor's theorem

$$c = c_o + \left(\frac{\partial c}{\partial y}\right)_o (y - y_o) + (\text{higher order terms})$$

where the subscript zero denotes a value at the origin. If the higher order terms are neglected, we have along the ray over the contour interval

$$\frac{\partial c}{\partial x} = 0 \qquad \frac{\partial c}{\partial y} = \frac{dc}{dy} = \text{const} = \left(\frac{\partial c}{\partial y}\right)_o = \frac{\Delta c}{\Delta y} \quad \text{.......} (3a,b)$$

and

$$\frac{D\theta}{Ds} = -\frac{\cos\theta}{c}\frac{dc}{dy} = -\frac{\cos\theta}{c}\frac{\Delta c}{\Delta y} \quad \text{.................} (4)$$

where the symbol Δ denotes the change in a variable across a contour interval, for example, $\Delta c = c_2 - c_1$ (the sign of Δc is negative if the ray proceeds from deep to shallow water). This "first" approximation is equivalent to the following assumptions: (1) The actual contours over a small interval are replaced by straight (parallel) contours with the mean trend. (2) The wave velocity varies linearly across the contour interval.

Equations (4) and (1b) may be combined to give an equation in c and θ, with the solution

$$\frac{\cos\theta}{c} = \text{const} = \frac{\cos\theta_1}{c_1} \quad \text{.....................} (5)$$

In terms of the angle $\alpha = \pi/2 - \theta$ between the wave front (crest) and the direction of the mean contour, we find

$$\frac{\sin \alpha_2}{c_2} = \frac{\sin \alpha_1}{c_1} \qquad (5a)$$

$$\frac{D\alpha}{Ds} = \frac{\sin \alpha_1}{c_1} \frac{\Delta c}{\Delta y} = \text{const} = \frac{\Delta \alpha}{\Delta s} \qquad (4a)$$

The two equations (5a) and (4a) together form the basis for the construction of wave rays. Equation (5a) has the same form as Snell's law. Equation (4a) shows that under the given assumptions the ray between adjacent contours is a circular arc and the equation constitutes a formula for the calculation of the curvature.

It is interesting to note that condition (4a) of constant curvature over an interval is precisely the basis of Kelvin's graphical method [WILLERS, 1948] for solving a second-order differential equation (to which set (1a,b,c) is equivalent). In fact, it would have been more appropriate from the mathematical point of view to start with the assumption that the ray is approximated by smoothly joining together circular arcs of appropriate curvatures. The calculation of the constant curvatures, to a first approximation, leads to the condition that wave velocities vary linearly over the interval. An adaptation of Kelvin's method to the construction of a ray is now considered.

Proposed procedure--The usual small curvature of wave rays precludes convenient construction with a compass of the actual circular arcs across contour intervals. The difficulty can be avoided by drawing tangents (Fig. 3, AP and PB) to the arcs and turning them through angles $\Delta\alpha$, or by drawing chords and turning them through angles $\Delta\alpha/2$. The angle $\Delta\alpha$ is computed from (5a) using $\alpha_2 = \alpha_1 + \Delta\alpha$. The following procedure, which uses tangents, is proposed for crossing the interval from a smoothed contour c_1 to a smoothed contour c_2 (see Fig. 4).

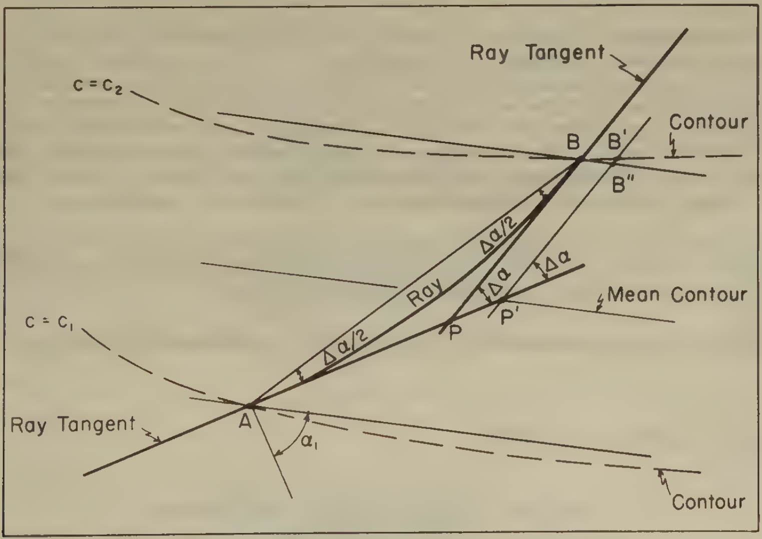


Fig. 3--Graphical solution by ray tangents

(1) Calculate the ratio c_1/c_2 by dividing the successive values of the ratio of wave speed at contour depth to wave speed in deep water which are obtained from tables [WIEGEL, 1948] or an alignment chart (see Fig. 5).

(2) Draw in a mean contour for the interval by eye.

(3) Extend the tangent at point A of c_1, which is known from the preceding interval, to intersection, P′, with the mean contour.

(4) On a perpendicular to tangent AP′ at P′, mark a turning point R such that P′R = 1 on some arbitrary scale.

(5) From R swing an arc of radius c_1/c_2, measured on the same scale, intersecting the mean contour at S.

(6) Construct the ray tangent at contour c_2 by drawing a perpendicular to SR such that AP equals PB as judged by eye.

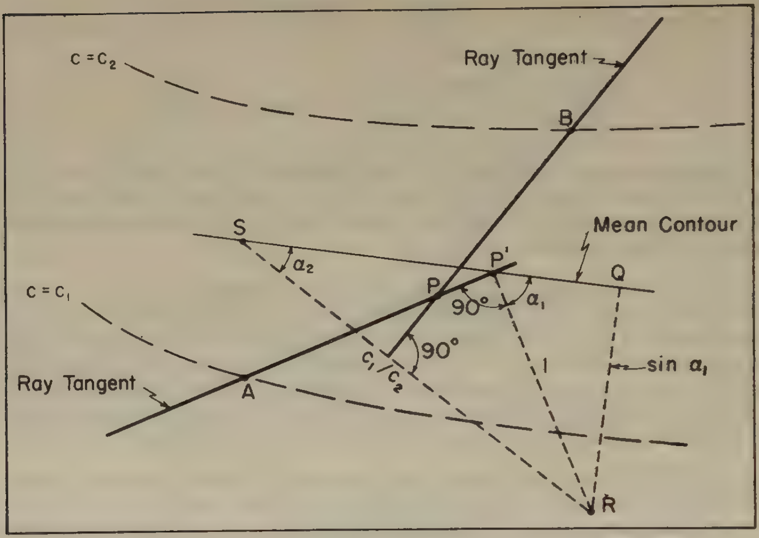


Fig. 4--Proposed method for construction of ray tangents

Steps 3-6 are rapidly carried out by use of a ray plotter (see Fig. 6), which is made of heavy plastic. The line labeled ray tangent is laid on the given tangent at contour c_1 so that the value of unity on the c_1/c_2 scale coincides with point P′ (Fig. 4). A pencil is inserted in the turning point and the plotter is turned until the scale intersects the mean contour at the value of c_1/c_2 computed for this interval in step 1. The left-hand edge of the plotter is now in the direction of the new tangent at c_2, but is not in the correct position. A straightedge is placed along the base of the plotter and the device is slid sideways until the left-hand edge passes through a point P with AP = PB. A line drawn through P along the left-hand edge is the required ray tangent at c_2.

To attain the desired accuracy, the limits $|\Delta c/c_1| < 0.2$ and $|\Delta\alpha| < 15°$ are suggested. If an excessive value of $\Delta\alpha$ is noted on the protractor scale at point P′ after the plotter is turned, an intermediate contour should be drawn and the steps repeated.

The proof of the construction (steps 1-6) is that in right triangles P′QR (Fig. 4)

$$RQ = \sin \alpha_1$$

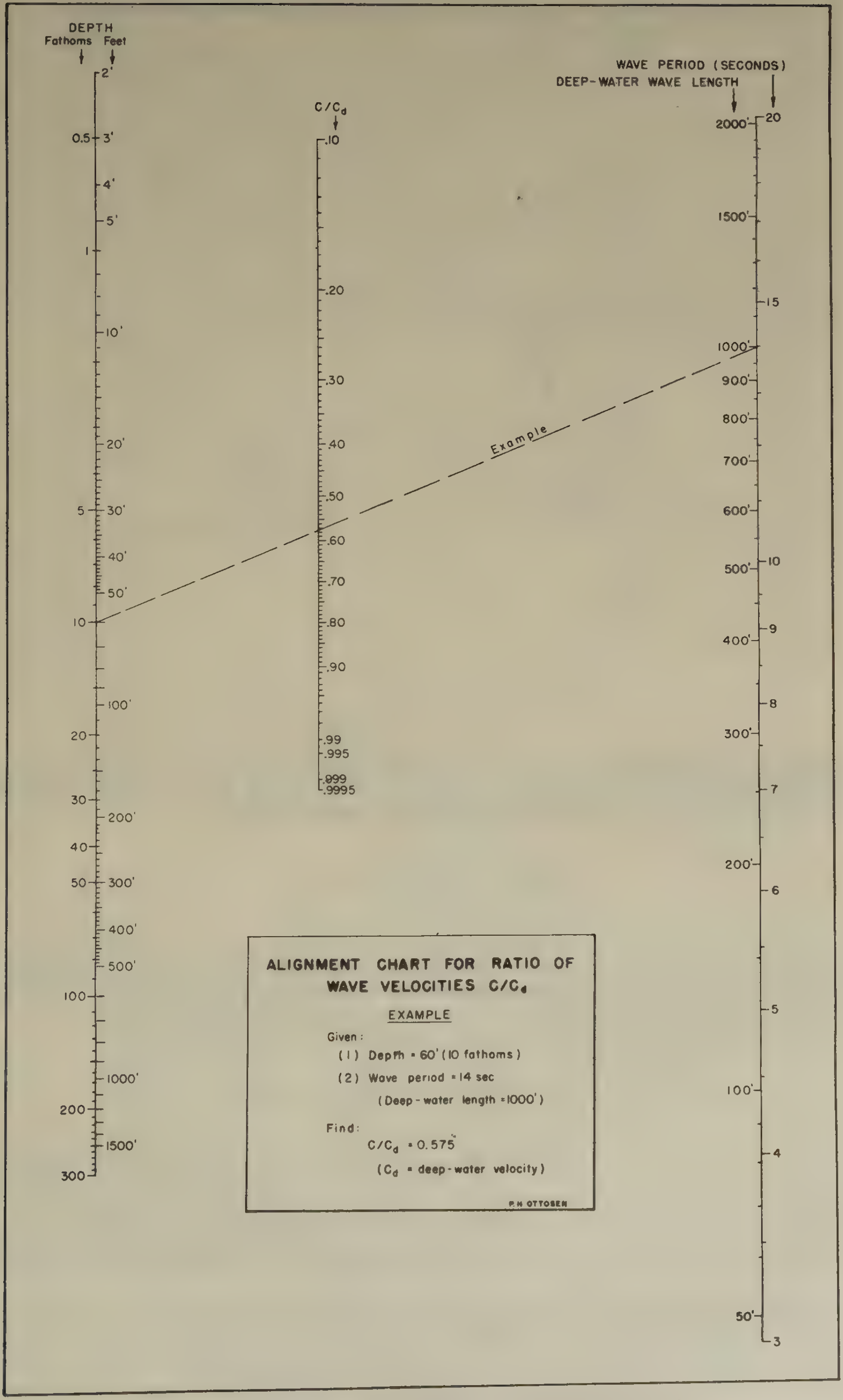
and, therefore, in right triangle SRQ

$$\sin \alpha_2 = \frac{RQ}{SR} = \frac{\sin \alpha_1}{c_1/c_2} = \frac{c_2}{c_1} \sin \alpha_1$$

as required by (5a). Tangents AP and PB are constructed equal as required for a ray of constant curvature (4a).

The ray plotter virtually eliminates the chances of turning off the tangents in the wrong direction [DUNHAM, 1951, p. 36], and no change in procedure is required to draw rays from shallow to deep water [SAVILLE, 1951], that is, for $c_2 > c_1$. However, special care must be exercised in applying (5a) when the ray becomes tangent to a bottom contour ($\alpha = 90°$) as in the following two cases: (1) where a ray proceeds from deep to shallow water and has a smaller curvature than the bottom contours, the ray reaches a point of tangency at some minimum depth (point T, Fig. 7), and then proceeds back to deeper water; (2) where a ray proceeds from shallow to deep water but is "totally reflected" by the deep water [ISAACS, WILLIAMS, and ECKART, 1951].

Whenever α approaches 90° (section ATB of the ray, Fig. 7), it becomes necessary to proceed in smaller steps by interpolating contours and to locate the point of tangency by successive approximations.



ALIGNMENT CHART FOR RATIO OF WAVE VELOCITIES C/C$_d$

EXAMPLE

Given:

(1) Depth = 60' (10 fathoms)

(2) Wave period = 14 sec

(Deep-water length = 1000')

Find:

C/C$_d$ = 0.575

(C$_d$ = deep-water velocity)

Fig. 5--Alignment chart for ratio of wave velocities c/c$_d$

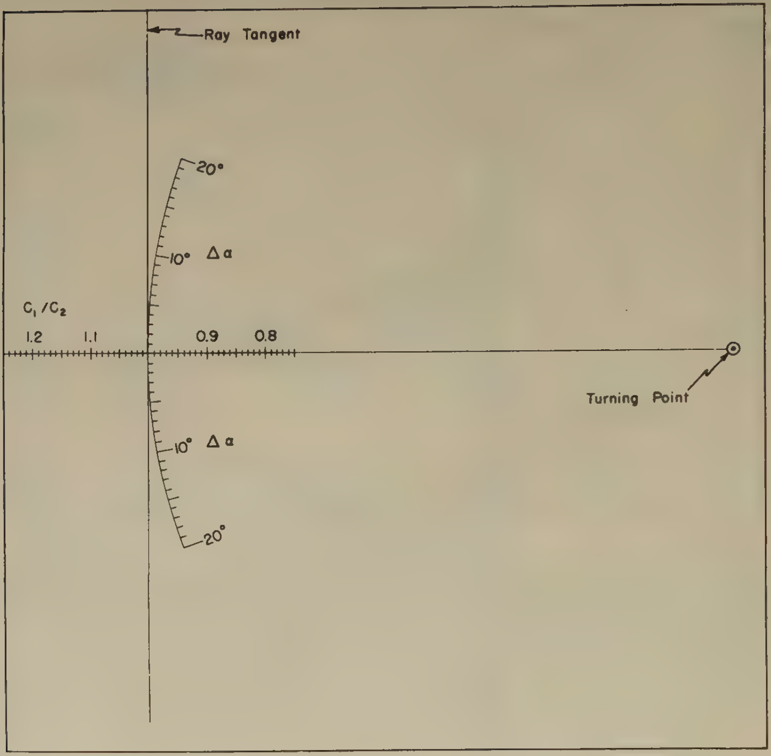


Fig. 6--SIO ray plotter

Since it is more difficult to maintain the precision of the triangle construction as α approaches 90°, an alternative method is suggested. From (4a), the change in direction of the ray over an arbitrary portion, δs, of the circular arc crossing a contour interval is

$$\delta\alpha = \frac{\delta s}{\Delta y} \cdot \frac{\Delta c}{c_1} \sin \alpha_1 \quad \text{(4b)}$$

where Δ refers as before to the change in a variable across the whole contour interval from c_1 to c_2. An assumed distance $\delta s/2$ is laid off along the initial tangent, the calculated angle $\delta\alpha$ is turned off, and the distance $\delta s/2$ is measured off to give the new point of tangency at the end of the portion of arc. As the construction is repeated, it is convenient to keep

$$\delta s = n \cdot \Delta y$$

where n is arbitrary but constant for the interval. Then

$$\delta\alpha \doteq n \cdot \frac{\Delta c}{c_1} \quad \text{(4c)}$$

and if $|\delta\alpha| < 15°$ and $\alpha_1 > 80°$, the combined errors in the approximation for $\delta\alpha$ amount to less than two per cent. The protractor on the ray plotter is used in turning off the calculated angle $\delta\alpha$. Further details of a similar construction are given in JOI.

The parallel movement of the plotter may be facilitated by incorporating a set of parallel rulers with the device. In the case of extensive use of charts with certain standard contours, it may be worth while to construct a series of plotters, one for each specified period, on which the c_1/c_2 scale is labelled in terms of the depth contours corresponding to c_1. Other time-saving devices will occur to the reader for any particular problem at hand.

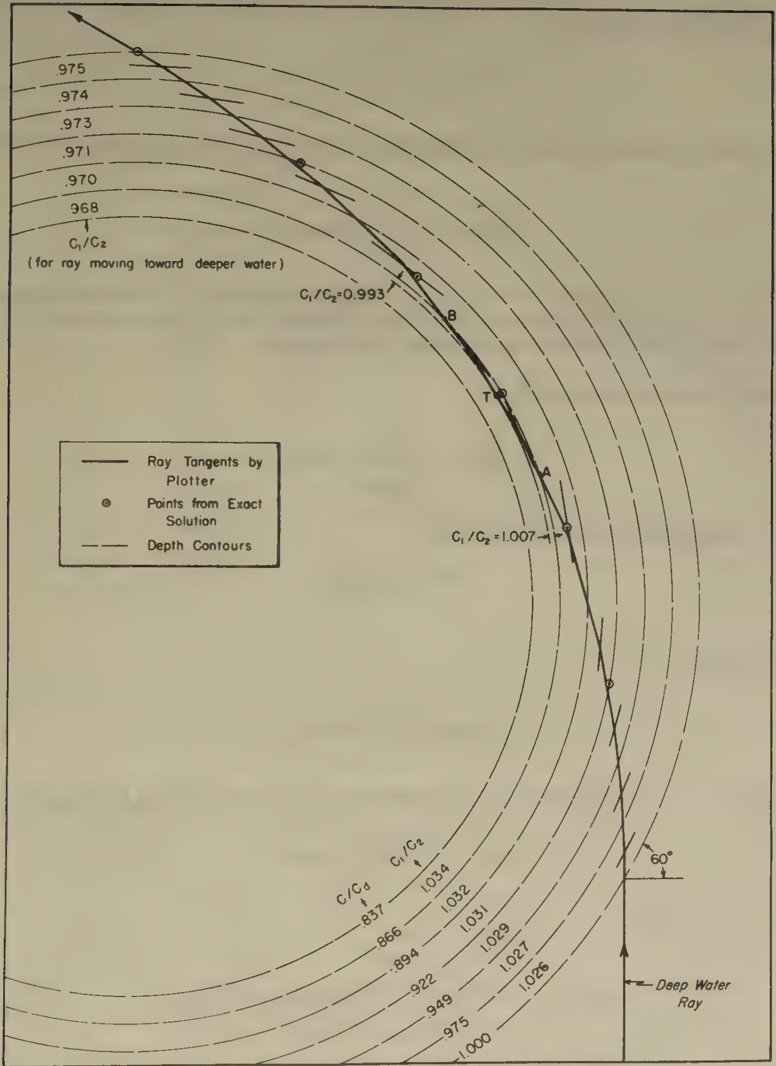

.975
.974
.973
.971
.970
968
C_1/C_2
(for ray moving toward deeper water)
C_1/C_2=0.993
B
T
A
C_1/C_2=1.007
Ray Tangents by Plotter
Points from Exact Solution
Depth Contours
C_1/C_2
C/C_d
.837
.866
.894
.922
.949
.975
1.000
1.034
1.032
1.031
1.029
1.027
1.026
60°
Deep Water Ray

Fig. 7--Comparison of proposed method of ray construction with exact ray solution for a special case of circular countours; wave velocity is assumed to increase as the square root of the contour radius to the maximum value c_d appropriate to deep water; exact solution is a parabola [ARTHUR, 1946]

Comparison with JOI--The principles underlying the proposed method are not at all original, but follow largely from JOI. There are, however, certain differences which may become important. Separate consideration is given to those arising from the theoretical bases of the two methods, and those involving differences in construction.

Theory--The JOI method is based on the equation

$$\Delta\alpha = \frac{R}{J}\cdot\frac{\Delta L}{L_{ave}}\cdot\sin\alpha_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(JOI 1)}$$

where

$$R = s_2 - s_1 \text{ and } J = y_2 - y_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

and $L_{ave} = (L_1 + L_2)/2$. This is derived from refraction principles, making use of the fact that the wave period remains constant.

$$T = \frac{L}{c} = \frac{L_1}{c_1} = \frac{L_2}{c_2} \quad \text{(7)}$$

Our (4a), which is derived from the differential equation of rays, together with (6) and (7) yields

$$\Delta\alpha = \frac{R}{J} \cdot \frac{\Delta L}{L_1} \cdot \sin \alpha_1 \quad \text{(8)}$$

which has the same form as (1) of JOI except for the occurrence of L_1 in the denominator instead of L_{ave}. This is a small and numerically unimportant difference for small values of $\Delta L/L_1$, but (8) is actually correct as stated and is evaluated more easily.

An equation comparable to (2) of JOI

$$\Delta\alpha = \frac{\Delta L}{L_{ave}} \tan \alpha_1 \quad \text{(JOI 2)}$$

is obtained by substituting the approximation

$$\frac{R}{J} \doteq \sec \alpha_1 \quad \text{(9)}$$

into (8) with the result

$$\Delta\alpha \doteq \frac{\Delta L}{L_1} \tan \alpha_1 \quad \text{(10)}$$

It is not necessary to introduce this approximation. If (5a) is solved for α_2, then

$$\alpha_2 = \sin^{-1}\left(\frac{c_2}{c_1} \sin \alpha_1\right) \quad \text{(5b)}$$

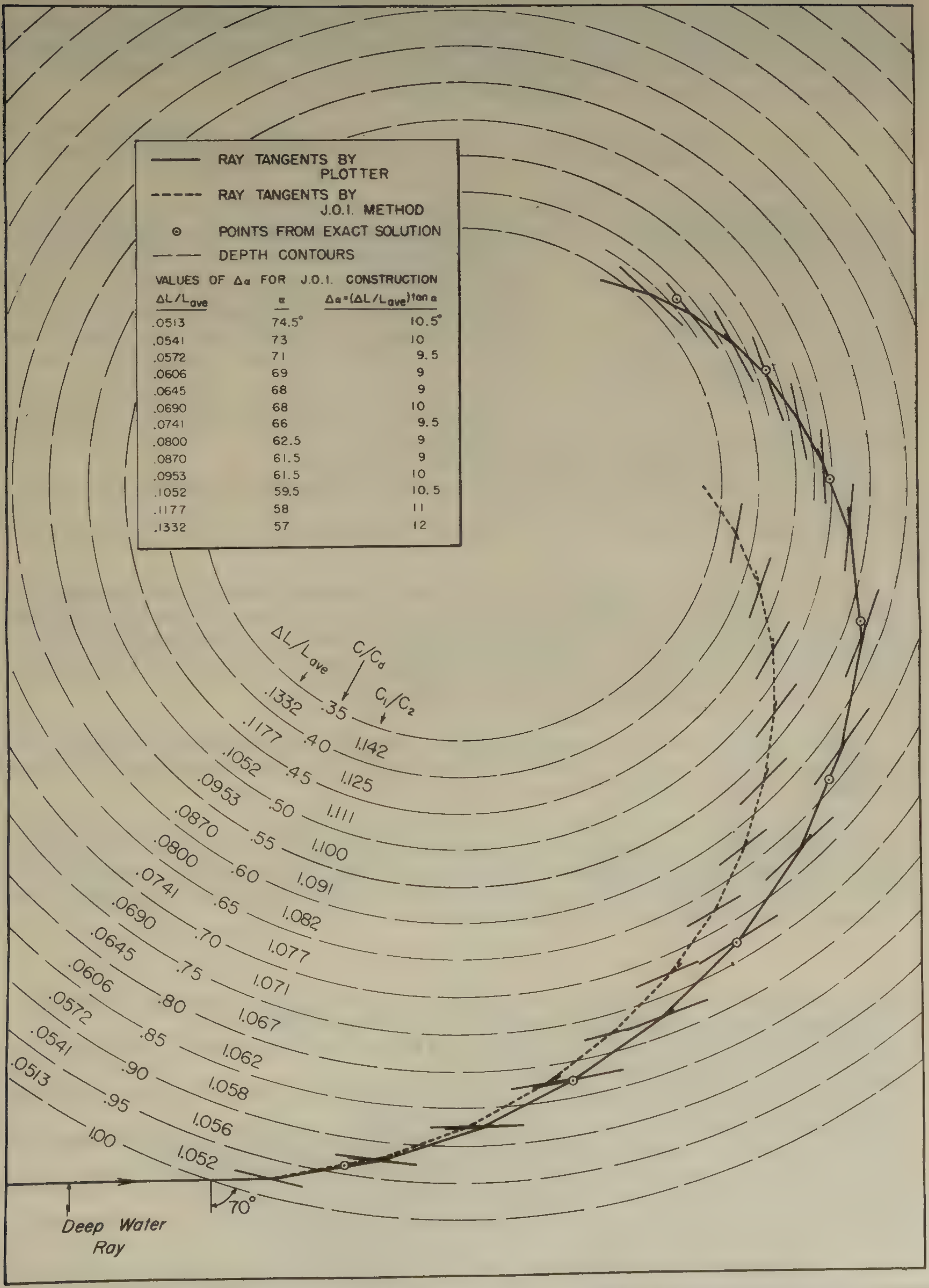
and since $c_2/c_1 = 1 + \Delta L/L_1$

$$\Delta\alpha = \sin^{-1}\left[\left(1 + \frac{\Delta L}{L_1}\right) \sin \alpha_1\right] - \alpha_1 \quad \text{(11)}$$

Table 1--Error in $\Delta\alpha$ resulting from approximate formula

$\Delta L/L_1$	α_1	$\Delta\alpha$ from (10)	Error
	°	°	pct
-0.05	77.6	-13	37
-0.10	66.2	-13	21
-0.15	56.6	-13	14

The errors in $\Delta\alpha$ resulting from the use of (JOI 2) may be excessive (see Table 1) even within the limits of $\alpha_1 < 80°$ and $|\Delta\alpha| < 13°$ stated in JOI. The error may be cumulative and becomes particularly important for extreme cases where α_1 remains large over many contour intervals (Fig. 8). The accuracy of the method is improved if the type I and type II protractors [JOI, 1948, pp. 30-31] are redesigned for the application of (8) and (11) instead of (JOI 1) and (JOI 2). (After presentation of this paper in May, 1952, the writers had the opportunity of examining a manuscript by T. Saville, Jr. and K. Kaplan, of the staff of the Beach Erosion Board. SAVILLE and KAPLAN [1952] have extended the derivation given by ISAACS [1944] to obtain equations which are more accurate than (JOI 1) and (JOI 2), and they have redesigned the refraction protractors.) As an alternative, an accurate construction can be made using only (JOI 1) or (8), but the protractor required is more complex [ISAACS, 1944]. Preparation of charts of bottom topography is simplified if the protractors are plotted in terms of c_1/c_2 instead of $\Delta L/L_1$.


RAY TANGENTS BY PLOTTER
RAY TANGENTS BY J.O.I. METHOD
POINTS FROM EXACT SOLUTION
DEPTH CONTOURS
ΔL/Lave
C/Cd
C1/C2
.1332 .35 1.142
.1177 .40 1.125
.1052 .45 1.111
.0953 .50 1.100
.0870 .55 1.091
.0800 .60 1.082
.0741 .65 1.077
.0690 .70 1.071
.0645 .75 1.067
.0606 .80 1.062
.0572 .85 1.058
.0541 .90 1.056
.0513 .95 1.052
1.00
70°
Deep Water Ray

VALUES OF $\Delta\alpha$ FOR J.O.I. CONSTRUCTION

$\Delta L/L_{ave}$	α	$\Delta\alpha = (\Delta L/L_{ave}) \tan \alpha$
.0513	74.5°	10.5°
.0541	73	10
.0572	71	9.5
.0606	69	9
.0645	68	9
.0690	68	10
.0741	66	9.5
.0800	62.5	9
.0870	61.5	9
.0953	61.5	10
.1052	59.5	10.5
.1177	58	11
.1332	57	12

Fig. 8--Comparison of proposed method of ray construction and JOI method with exact ray solution for a special case of circular contours; wave velocity is assumed to increase linearly with contour radius to the maximum value c_d appropriate to deep water; exact solution is a logarithmic spiral [ARTHUR, 1946]

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On Uniform Group Endings

In his judicious and forceful discussion, "For and Against Uniform Endings in Zoological Nomenclature," in the opening number of SYSTEMATIC ZOOLOGY (pp. 20-23), George Gaylord Simpson pays particular attention to the recent proposal by H. B. Stenzel (*Science, 112,* 94, 1950) that nine uniform name endings be adopted for ordinal (-ica, -ida, -ina), familial (-icae, -idae, -inae), and tribal (-ici, -idi, -ini) groups. This scheme has also been criticized by Alvarez (*Ciencia, 11,* 279-280, 1952).

Stenzel's proposal is so alluring in its simplicity, consistency, and logic as to inspire, on first thought, agreement and adoption. It received support, for example, from the American Society of Ichthyologists and Herpetologists at its 1951 meeting, particularly from the ichthyologists present, the writer included (the herpetologists were particularly opposed to the abandonment of their relatively few and well-known ordinal names).

On more thoughtful and analytical consideration, Simpson points out how confusion and even error might well arise from the acceptance, for groups of different rank, of names so very similar as Hominica, Hominida, Hominina, Hominicae, Hominidae, Homininae, Hominici, Hominidi, and Hominini. I would like to bring to the attention of systematic zoologists a more serious defect of Stenzel's proposal, namely, that it would deprive us of the use, now frequent and desirable, of definitive group names in adjectival and derived substantival form, or would throw such usage into hopeless confusion. Thus, if we should write about "poeciliid" fishes (or gonopodia, or life-history), or of the distribution, genetics, or anatomy of the "poeciliids," it could not be known, under the system advocated by Stenzel, whether reference was to the order Poeciliida, the family Poeciliidae, or the tribe Poeciliidi. Under the current system we write about cyprinodonts (or poecilioids, or microcyprines), poeciliids, and poeciliins, when referring respectively to order, family and tribe (the subfamily adjective is poeciliine).

It would, of course, be possible to devise a system of uniform group-name endings, through at least the ordinal series, that would be less confusingly alike and would permit the derivation of distinctive adjectives (and of the corresponding vernacular substantives). Objections raised specifically to the system of Stenzel could thus be avoided. Other objections, such as that of supplanting literature-filled and familiar group names, would remain. An additional and fundamental disadvantage of the Stenzel proposal, or of any similar system of boxing the zoological compass, seems to me to be the inherent emphasis on group ranking, which I regard as a particularly subjective, superficial, and inconsequential (though perhaps not altogether unavoidable) aspect of taxonomic work.

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ANTITROPICAL DISTRIBUTION OF FISHES AND OTHER ORGANISMS(¹)

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WHEN naturalists travel from their home lands and waters in the North Temperate Zone to South Temperate regions, as many of us recently have, they are struck first by the bewildering abundance of strange life in the tropics and are then impressed, as they enter the refreshingly cooler regions still farther southward, by the reappearance of certain familiar types of plants and animals. True, these forms are mixed with strange organisms, but it is the familiar ones that engender the depth of feeling that comes with the reunion of old friends.

Since it first attracted the attention of travellers from Europe to far southern lands this phenomenon has been called " bipolar distribution " or " bipolarity," and has been variously explained. One of the theories, that of separate creation, might now be modified into one of independent adaptive evolution. Another idea has been that the similar forms of north and of south are relicts, which stemmed from a cosmopolitan biota of an early Tertiary period of relatively warm and uniform world climate. On this theory the disjunct populations were forced apart by the increasing heat of the Tropics and by competition with a recently evolved rich tropical biota. Still another concept is that the Tropics have been crossed and to some extent are still being crossed, along isothermal lines, the marine forms dipping into the cold deep sea and the land forms rising to cold mountain heights. Advocates of continental drift have found in their aberrant hypothesis an explanation of bipolarity, as well as of almost every other phenomenon of biogeography.

A more recent and in general more plausible explanation, stressed by Berg (1933), is that the Tropical waters were transgressed during the Pleistocene periods of global cooling. This is the theory to which I particularly subscribe, though I recognize that each alternative explanation mentioned (with the exception of local creation) could be supported by an impressive array of evidence and has probably been valid to some degree for some groups.

In line with this theory of Pleistocene interchange of faunas across the Equator we find, on examining a large body of evidence, that the phenomenon with which we are dealing is only in a very small degree one of bipolarity. As Berg (1933) stressed, the vast majority of the related forms of life that occur on either side of the Tropic Zone, but not within it, inhabit moderate rather than high latitudes. Among marine fishes, as Norman (1938) showed, the Antarctic contains only a small percentage of groups or of species of Arctic relationship. A few forms may be cited as definite examples of truly bipolar distribution ; a much larger number may better be called biboreal or bitemperate, and those that are bitemperate are warm-temperate as well as cool-temperate. Furthermore, a

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(¹) Contributions from the Scripps Institution of Oceanography.

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considerable number of subtropical types are more or less completely separated by the tropical biotas. The phenomenon with which we are dealing is not one of special resemblances between polar elements but rather one of narrow to broad, incomplete to complete equatorial discontinuities in the latitudinal distribution of plants and animals. It therefore seems desirable that we stop expressing ourselves and thinking in terms of " bipolar distribution " and that we adopt another term—I suggest " antitropical "—to apply to the forms of life that shun the Tropics (the term to apply also to this type of distribution). " Bipolarity " would then become " antitropicality."

There are many patterns of antitropical distribution, because resemblances exist between polar, boreal, cool-temperate, warm-temperate, and even subtropical forms of life ; because the breaks occur along all the main coast-lines that cross the Tropics ; and because the many bitemperate complexes embrace various combinations of two or more temperate biotas (perhaps less than half of the bitemperate series could rightly be classed in the " pantemperate " category, to which I have occasionally referred). These various patterns could be illustrated by different groups of organisms, but I shall largely restrict my discussion to the marine fishes, with which I am most familiar.

The bipolar pattern, as already indicated, involves relatively few fishes. In the Antarctic and subantarctic regions there occur, mixed with a much larger number of endemic types, a few species of families that are otherwise chiefly of Arctic or subarctic range—slime-eels (*Myxine*), skates (*Raja*), and hakes (*Merluccius*) ; also certain cods (Gadidæ), sculpins (Cottidæ), lump-fishes (Cyclopteridæ), snail-fishes (Liparididæ), seapoachers (Agonidæ), and eelpouts (Zoarcidæ and Lycodapodidæ) (Norman, 1937, 1938). In the far south there are several species of *Raja* and a moderate number of zoarcids, but the other bipolar groups are each represented there by only one or a very few species. These Antarctic and subantarctic types seem to have been derived from the far north, where the same groups are much better developed. Most, perhaps all, were probably derived by isothermal dispersal, perhaps in part during Pleistocene periods when lesser depths would probably have been required in the transgression of the Tropics. The tropical crossings were probably chiefly effected along the western shores of the two great oceans. Indeed, as a result of the exploration of the United States Fish Commission vessel " Albatross," Garman (1899) disclosed in the region of Panama living deep-sea representatives of half the fish groups here listed as bipolar—namely, *Myxine*, *Raja*, *Merluccius*, Liparididæ, and Zoarcidæ. Some of the bipolar fish sets may retain an isothermal connection, as certain invertebrates almost surely do. The varying degree of differentiation displayed by the Antarctic representatives of far northern groups bespeaks widely different periods of isolation. The evidence of relationships and of paleichthyology, however, argues against the pre-Tertiary transtropical dispersal of the groups named above.

Several subantarctic or south-boreal fishes commonly included in the " bipolar " category appear, in contrast, to be ancient, probably pre-Tertiary relicts of groups that have failed to persist in the Tropics, either because of unfavourable physical conditions or because they were unable to compete with the rich faunas that have evolved there. In this category I would include, among fishes, the following fluviatile, anadromous, and catadromous types: (1) the southern lampreys, comprising the genera *Mordacia* and *Geotria*, each referable to a family distinct from the Holarctic Petromyzontidæ, and the distinctive and primitive teleost families Galaxiidæ, Aplochitonidæ, Retropinnidæ, and Prototroctidæ. Their trenchant separation from not clearly recognizable Holarctic representatives indicates prolonged isolation.

A few other primitive teleosts, notably the subantarctic herrings usually retained in the genus *Clupea*, may be pre-Tertiary or early Pleistocene relicts, for they are of ancient lineage. Their degree of differentiation and their far-southern habitat suggest isolation since one of the earlier, intense periods of Pleistocene glaciation.

Bitemperate fish types not only outnumber the bipolar, but also, as a rule, exhibit less differentiation and appear to have had their populations disrupted by tropical waters for a briefer period. The species that exhibit no measured differences on the two sides of the Tropics and those that are only incipiently or weakly differentiated have probably been segregated into northern and southern populations only since late Pleistocene.

Many of the bitemperate types—and among these we might better include some of those here listed among the bipolar—may have crossed the Tropics, perhaps chiefly in Pleistocene times, by descending into deeper water. This is particularly probable for various more or less strictly bitemperate types of sharks, including the genera *Hexanchus*, *Heptranchias*, *Notorhynchus*, *Heterodontus*, *Cephaloscyllium*, some other scyliorhinids, *Galeorhinus*, *Mitsukurina*, *Carcharias*, *Lamna*, *Tetroras* [*Cetorhinus*], *Somniosus*, and *Echinorhinus*, and certain species-groups of *Mustelus* and *Squalus*. Other bitemperate fish types that may have transgressed the Tropics by a deep-water isothermal route during the Pleistocene are the hagfish genera *Eptatretus* and *Polistotrema*; the john-dory (*Zeus*), an example of wide-spread Old World antitropical distribution; also, in the Eastern Hemisphere, various gurnards (Triglidæ), sinistral flatfishes (Bothidæ), and other groups; in the eastern Pacific, such genera as *Cheilotrema*, *Pimelometopon*, *Caulolatilus*, and *Sicyogaster*; the scorpænid genus *Sebastodes*, a speciose North Pacific genus of which one species group has populated waters from Peru to Cape of Good Hope; *Oplegnathus*; and certain clinids.

Many other antitropical fishes of the Temperate Zones, including most of the pantemperate types, have attributes that lead us to believe that they crossed the Tropics when the surface waters were considerably cooled, presumably during late Pleistocene time. Ecologically, they are surface-bound; therefore incapable of transgressing equatorial water by the cool deep-water route. That they crossed the Tropics during the last cold period of the Pleistocene is suggested by their incipient speciation.

In this category of surface-bound recent transgressors of the Tropics we must include such shore-pelagic fishes as the sardine or pilchard genus *Sardinops* (of California, Japan, Peru and Chile, Australia and New Zealand, and South Africa); the roundherrings of the genus *Etrumeus* (of the western North Atlantic, California, Hawaii, Japan, Australia, and South Africa); the anchovy genus *Engraulis* (of Europe, Japan, South Africa, and Australia and New Zealand); the similar anchovies of

California, Peru and Chile, and Argentina, which, as I shall presently show, constitute a distinct genus; the even more strikingly pantemperate jackmackerel (*Trachurus*) and chub mackerel (*Pneumatophorus*) groups; the saury genus *Scomberesox* (of North Atlantic and South Temperate waters); the species of *Seriola* related to *S. dorsalis*; *Centrolophus*; several tunas (Thunnidæ) and tuna-like fishes; also *Alepisaurus* and various other rather pelagic types.

As emphasized by Berg (1933), not only these fishes, but also various other organisms almost certainly had a surface-water connection between the northern and southern hemispheres at a geologically very recent time, very probably, in large part, during the last period of continental glaciation. Notable examples are sealions (Otariidæ), right whales (*Eubalaena*), and the giant kelp *Macrocystis*, which is said to be represented in both hemispheres by the same two ecotypic varieties of a single species.

Zoogeographical, paleontological, and oceanographical data keep accumulating to force the conclusion that the last period of glaciation was synchronous in the two hemispheres and that the isotherms of sea and land were then markedly displaced equatorward. The increased winds from polar toward equatorial regions must have accentuated the convergence of the cool currents, along the eastern shores of the two great oceans. The tropical belt must have been narrowed and considerably cooled everywhere. Paleontological data from Europe and Africa, the occurrence of a land-locked salmon (*Oncorhynchus*) in Formosa, and the ichthyological data in the following paragraphs are samples of the evidence on which these statements rest.

The paucity of the Panamanian marine fish fauna, particularly among the reef fishes, suggests widespread extermination by a marked cooling of the tropical eastern Pacific. This fauna is outstandingly rich only in certain families that characteristically inhabit mud and sand bottom, notably the drums (Sciaenidæ), marine catfishes (Ariidæ), and anchovies (Engraulididæ). A decimated reef fauna would nicely explain the obviously very recent establishment on the tropical American Pacific Coast, particularly on the outlying islands, of Indo-Pacific fishes. The broad intervening expanse of open water, stressed by Ekman (1935) as the most notable barrier in the circumtropical distribution of life, has no doubt allowed only rare strays to reach America from Oceania. Had they reached shores as saturated with life as are those of the Indo-Pacific area it is hardly conceivable that these strays could have established populations.

The former cooling of now essentially tropical waters, about the Cape region of Baja California, is indicated by the entrapment, in the upper part of the Gulf of California, of a rather large faunal element related to that of north-western Baja California and southern California. Most of the constituent types are no longer able to round the tip of the peninsula. The varying differentiation of the Gulf representatives, generally very slight and still unmeasured for some species, suggests the origin of these upper-Gulf types during several periods of Pleistocene global cooling, but chiefly during the last ice period. Somewhat similarly, the occurence in the Galápagos Islands of many Temperate Peruvian types, in part more or less differentiated, suggests transfer and establishment during Pleistocene periods of general oceanic cooling.

The occurrence of European types in South Africa, undifferentiated or weakly differentiated, and of Japanese types not only in South Africa but also in Australia, in similar stages of speciation, suggests that the Pleistocene cooling of the oceans was world wide. Even the vast Indo-Pacific area appears to have been cooled sufficiently to permit the passage of a limited representation of the warm-temperate fauna, though insufficient to exterminate any considerable part of "the great mother fish fauna of the world."

Combining certain zoogeographical and oceanographic data, and accepting the strong evidence that the temperature relations of organisms are very conservative, we may infer the approximate amount to which certain tropical waters were cooled during the late Pleistocene, to allow the transgression of the Tropics by such fishes and other organisms. The evidence is particularly strong and uncomplicated for the long and nearly straight shore of the eastern Pacific, where, it is commonly assumed, the cool-water faunal connections were especially numerous. Along this coast many of the now disrupted forms, such as the sardine and the giant kelp, are separated by a tropic belt that extends from near Cape San Lucas (the tip of Baja California) to the northern limit of the Humboldt or Peru current, in Peru. The almost certainly late Pleistocene faunal connection between these present limits would, we may assume, have required the cooling of the ocean surface to approximately the temperature now prevailing in the region from Cape San Lazaro to Cape San Lucas—that is, off Magdalena Bay, Baja California. The surface temperature data averaged monthly for coastwise squares of 5° latitude and longitude indicate for this region a fluctuation from about 18° c. in the spring to about 25° in the summer, and for the warmest area intervening between this region and the sharp gradient in Peru, a change from 26·5° in the winter to 28° in May. The difference between the monthly averages is about 8·5° for the coldest month and 3° for the warmest. Since, toward the warm end of their ranges, most cool-water forms breed in the coolest season, it is probable that during winter in the last Ice Age the surface of the shore waters of the eastern Pacific was cooled in the order of 8°, though not necessarily more than about 3° during the warmest month. That there was some cooling during the summer is suggested not only by the general data, but also by such facts as this: that the tuna clippers are unable to keep sardines alive at temperatures much above 26°. The decrease of about 8° in winter would account for the presumed annihilation during the late Pleistocene of much of the fish life of the Panamanian region, but not of all the fauna, for there is a large tropical representation about Magdalena Bay, where winter temperatures run low.

Similar, though less definite, data for the western Pacific indicate that the equatorial waters there were cooled during the Pleistocene, but probably not more than 2° to 4° during any month. There is little evidence of extensive cooling of the western Atlantic Tropics during the Pleistocene, but in all probability the convergence of the isotherms and the equatorial cooling was very pronounced along the eastern shores of the Atlantic.

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SUMMARY OF DISCUSSION

Professor Yonge cited as an example of the ease with which temperate forms traverse tropical regions, the recent appearance of the New Zealand barnacle *Elminius modestus* in docks in Britain. Further, he inquired whether a full analysis had yet been published of the situation in the upper part of the Gulf of California where an isolated population is locked in, corresponding to that of the same latitude outside, but differing from that at the opening of the gulf. An analysis was still being made and would shortly appear in published form, it was stated.

Dr. Johnson mentioned the extraordinary case of barnacles being transported overland to the Salt Lake of Utah. Mr. Powell stated that Dr. Hubbs had very conclusively answered the question to be raised by him in his paper following, as to whether some bipolar animals may or may not go deep in the tropics and as to routes of convergence followed between north and south.

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